2009-06

Climate analysis and long range forecasting of dust storms in Iraq

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MONTEREY, CALIFORNIA

THESIS

CLIMATE ANALYSIS AND LONG RANGE FORECASTING OF DUST STORMS IN IRAQ

by

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June 2009

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** June 2009	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE Climate Analysis and Long Range Forecasting of Dust Storms in Iraq	**5. FUNDING NUMBERS**
6. AUTHOR(S) Jacquelyn C Crook	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT	**12b. DISTRIBUTION CODE**
Approved for public release; distribution is unlimited	A

13. ABSTRACT (maximum 200 words)

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14. SUBJECT TERMS Iraq, Climatology, Long Range Forecast, Composite Analysis Forecast (CAF), Dust, Military Operations, Climate; Seasonal Forecast; Shamal; El Nino; La Nina; Precipitation Rate; Statistical Forecast	**15. NUMBER OF PAGES** 85
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY AND PHYSICAL OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

Skillful long range forecasts of dust storms have the potential to be very useful in planning operations by the Department of Defense (DoD) and other organizations. Our study assessed the potential to predict Iraq dust storms at long lead times (e.g., several weeks to several months). We examined two variables that associated with dust storms: precipitation rate and surface winds. To characterize conditions during dust storms, we generated averages (conditional means) of Iraq precipitation prior to, and winds during, dust storms, as well as the anomalies in those variables compared them to their long term means. We then identified statistically significant correlations between those Iraq variables and remote climate system variables. Those correlations were used to develop two long range predictors of dust favorable precipitation and winds in Iraq: (a) sea surface temperature in the Indian Ocean; and (b) an index of the difference between sea level pressure near Tunisia and Kazakhstan (an indicator of surface winds). We used these predictors in an adaptation of the composite analysis forecast (CAF) method to hindcast and forecast dust favorable conditions in Iraq at lead times of one and two months. Verification of our results indicates that our method has a high potential for producing skillful long range forecasts of the potential for dust storms in Iraq.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFWA	Air Force Weather Agency
AG	Arabian Gulf
AMJ	April-May-June
AN	Above Normal
AOR	Area of Responsibility
BN	Below Normal
BonD	Battlespace on Demand
CAF	Composite Analysis Forecast
CARMA	Community Aerosol Research Model for Atmospheres
CENTCOM	Central Command
CFDL	Coastal Fluid Dynamics Laboratory
CFS	Climate Forecast System
CIA	Central Intelligence Agency
COAMPS	Coupled Oceanographic and Atmospheric Mesoscale Prediction System
COMET	Cooperative Program for Operational Meteorology, Education and Training
CNMOC	Commander, Naval Meteorology and Oceanography Command
CPC	Climate Prediction Center
DoD	Department of Defense
DTA	Dust Transportation Application
ECMWF	European Centre for Medium Range Weather Forecasts
EN	El Niño
ENLN	El Niño/La Niña

ESRL	Earth Systems Research Laboratory
GPS	Global Positioning System
hPa	Hecto-Pascal
IO	Indian Ocean
IOZM	Indian Ocean Zonal Mode
IRI	International Research Institute for Climate and Society
JAS	July-August-September
JFM	January, February, March
JHU/APL	The Johns Hopkins University Applied Physics Laboratory
LN	La Niña
LTM	Long Term Mean
METOC	Meteorology and Oceanography
MJO	Madden-Julian Oscillation
MM5	PSU/NCAR Mesoscale Model
NAAPS	Navy Aerosol Analysis and Prediction System
NAO	North Atlantic Oscillation
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Center for Environmental Prediction
NN	Near Normal
NOAA	National Oceanic and Atmospheric Administration
NOGAPS	Navy Operational Global Atmospheric Prediction System
NRL	Naval Research Laboratory
OCDS	Operational Climate Data Summary
OIF	Operation Iraqi Freedom

OND	October-November-December
PFJ	Polar Front Jet
PR	Precipitation Rate
PSU	Pennsylvania State University
SLP	Sea Level Pressure
SOP	Standard Operating Procedure
SST	Sea Surface Temperature(s)
STJ	Subtropical Jet
TKI	Tunisia Kazakhstan Index
TOMS	Total Ozone Mapping System
USAF	United States Air Force
USGS	United States Geological Survey
WPAC	Western Pacific Ocean
WRF ARW	Weather Research and Forecasting, Advanced Research WRF
WS	Weather Squadron

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ACKNOWLEDGMENTS

First, I would like to thank my two advisors, Dr. Tom Murphree and CDR Rebecca Stone. Their knowledge, patience, and guidance through this process are immensely appreciated.

My thanks also goes to the additional personnel who helped with this research endeavor. They include Capt Sarah Moss, USAF, and her personnel at the 14th Weather Squadron; Annette Walker and other members of the aerosols group at the Naval Research Laboratory, Monterey; and David Meyer, Mary Jordan and Bob Creasey at the Naval Postgraduate School (NPS).

I would also like to extend my thanks to my fellow METOC students here at NPS for their ideas, encouragement, and support.

Finally, I would like to thank my family for their love and support and always putting a smile on my face when I needed it.

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I. INTRODUCTION

A. BACKGROUND

One of the most well-known military strategists, Sun Tzu, states in *The Art of War* "Know the enemy, know yourself; your victory will never be endangered. Know the ground, know the weather; your victory will then be total." Throughout history, the natural environment has had a critical role in military operations. Effective military commanders know the environment and the effects it has on their missions, personnel, and their adversaries.

The Joint Doctrine, Tactics, Techniques, and Procedures for Meteorological and Oceanographic (METOC) Operations (Department of Defense 2008) stresses:

> The principles of accuracy, consistency, relevancy and timeliness are the cornerstone of joint METOC operations. Properly applied, joint meteorological and oceanographic operations can provide air, land, maritime, space, and special operations forces with a significant, even decisive, advantage over our enemies.

The Battlespace On Demand (BonD) concept developed by the Commander, Naval Meteorology and Oceanography Command (CNMOC) lays out a strategy for achieving decision superiority for the warfighter through the exploitation of information about the battlespace environment (Evans 2008). Figure 1 is a graphical explanation of the BonD concept depicting three tiers of information and support provided by METOC community to warfighters. Tier 0, the foundation of the pyramid, contains environmental data from satellites, ground stations, buoys, radiosondes, and other data sources. Tier 1, the second building block in Figure 1, contains forecasts of the environment based on analyses and predictions derived from Tier 0 data. Tier 2 contains METOC products that predict how the environmental conditions described by Tier 1 affect the performance of warfighter and adversary sensors, platforms, personnel, and

systems. Tier 3, at the top of the pyramid, contains METOC products that recommend to warfighters how to best use the information form Tiers 0-2 to manage the risks and opportunities presented by the predicted environment. The BonD concept summaries how METOC support provide a range of actionable environmental analyses and forecasts, as well as recommendations on force allocation and employment that directly enhance safety and warfighting effectiveness (Evans 2008).

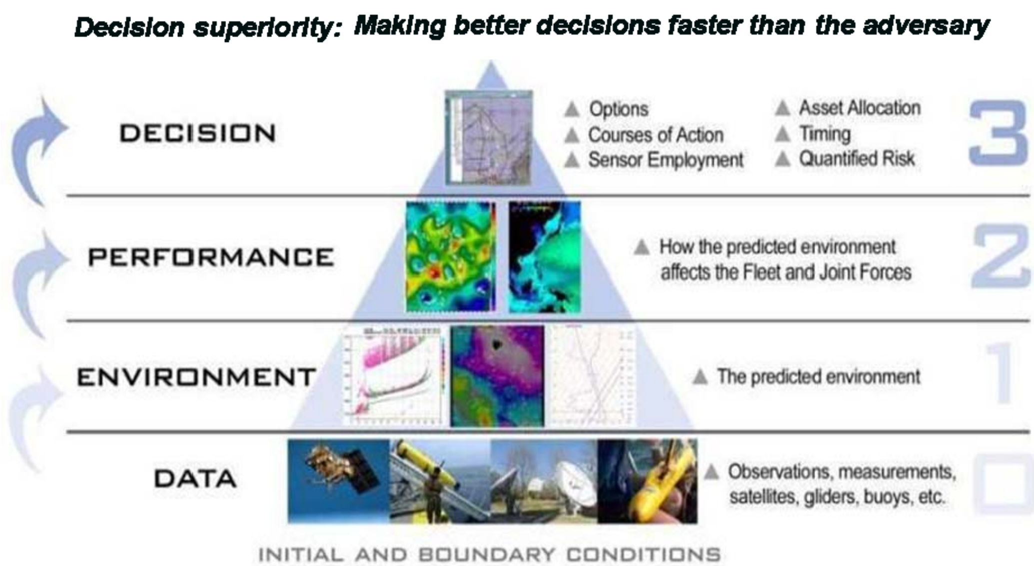

Figure 1. Battlespace on Demand (BonD) Concept of Operations for the Navy Meteorology and Oceanography (METOC) Community. Adapted from Evans (2008).

The U.S. military has been conducting operations for several decades in southwest Asia and other parts of the Central Command (CENTCOM) area of responsibility (AOR). One of the constants in the southwest Asia region, and Iraq in particular, is the occurrence of dust storms. Dust storms can have a significant impact on military operations. During the Operation EAGLE CLAW hostage rescue attempt in Iran in April 1980, strong dust storms were a critical factor in mission failure (Radvanyi 2002). A significant dust storm affected operations at

the beginning of Operation Iraqi Freedom (OIF) in Iraq in late March 2003 (Hinz 2004). Figure 2 shows the scheduled and canceled OIF aviation sorties during 17 March–12 April 2003. The spike in canceled sorties due to weather during 25–28 March 2003 coincided with the late March 2003 Iraq dust storm and is one indication of the operational impacts of that dust storm.

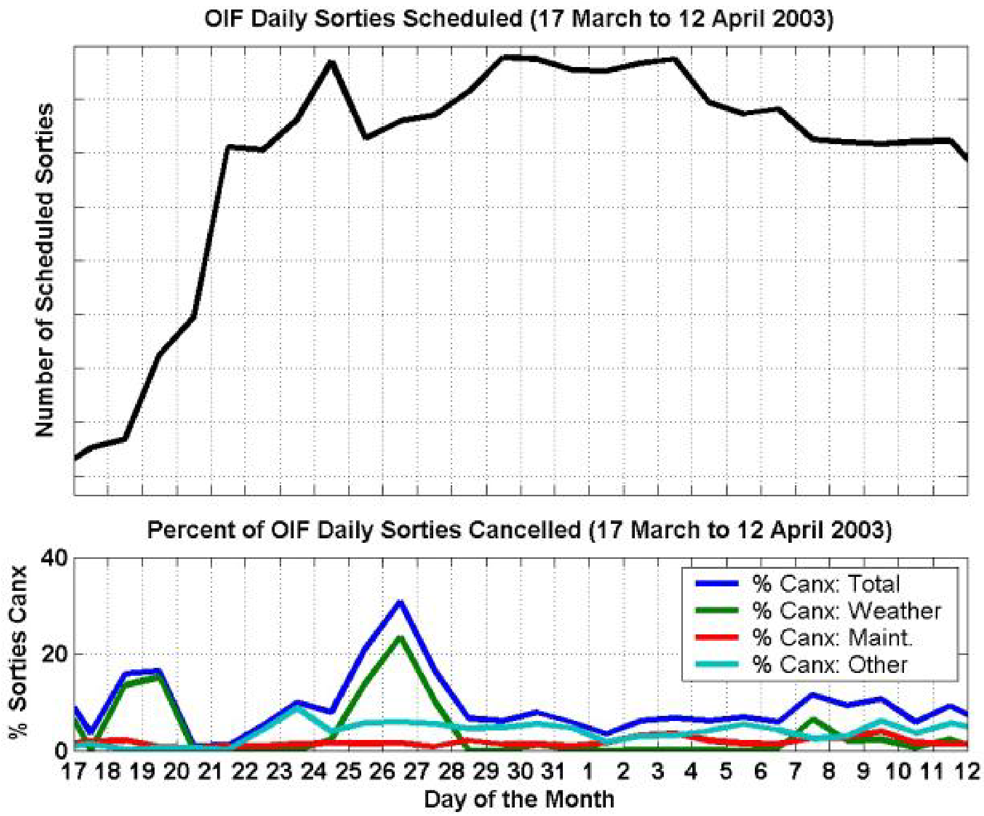

Figure 2. Number of scheduled sorties and percentage of sorties canceled during approximately the first month of OIF. Notice the spike in canceled sorties due to weather is during a period of significant dust blanketing the region. From Hinz (2004).

Dust storms can ground aviation operations because of reduced surface visibility for takeoffs and landings, and at the target. Dust storms can also lead to failure of aviation strike missions due to effects on missiles' flight and navigation instruments as well as global positioning system (GPS) guidance systems. Dust

storms affect logistics missions as well, particularly due to small dust particles getting into machinery, command and control equipment, and the effects of dust on the health of personnel.

B. GEOGRAPHY OF IRAQ

The area of Iraq is 437,072 sq km, approximately the size of California, or twice the size of Idaho (CIA Fact Book, accessed 14May2009). Iraq borders the countries of Kuwait, Iran, Turkey, Syria, Jordan, and Saudi Arabia, which are also dust source regions (Figure 3). Iraq and these neighboring countries all have significant sources of dust for dust storms in Iraq.

Figure 3. Iraq and surrounding countries. Figure from CIA World Fact Book

As shown in Figure 3, the Iraq major rivers are the Tigris and Euphrates rivers, flowing northwest to southeast before merging into the Shatt-Al-Arab and flowing into the Persian Gulf, also known as the Arabian Gulf (AG). Other significant bodies of water nearby are the Mediterranean Sea, Black Sea, and Caspian Sea.

Figure 4 shows the topography and major geographic provinces of Iraq. The Zagros Mountains extend up to 3000 meters in Iraq and form a natural border between the northeast region of Iraq and western Iran. The Taurus Mountains form the border between northern Iraq and southern Turkey. Precipitation reaches a maximum in the mountain ranges and is a critical water source for the rest of Iraq. The leeward (generally eastern) sides of the mountain often get half or less of the precipitation of windward (generally western) sides. The majority of Iraq is below 300 meters in elevation. The Syrian Desert comprises the western area of Iraq, and desert comprises approximately 58% of the total area (14^{th} WS 2009). The central and southern regions of Iraq are primarily composed of alluvial plains and desert valleys. Marshlands exist between the Tigris and Euphrates rivers. Significant portions of these marshlands are currently dry due to natural and manmade causes, and the recently exposed marsh bottoms are now a significant source of dust within Iraq (Walker 2005, Earth Observatory 2001).

Figure 5 shows dense marsh vegetation (mainly phragmites, or marsh grass) appears as dark red patches in 1973–1976. The image taken in 2000, in Figure 5, shows most of the Central Marshes appear as olive to grayish-brown patches indicating low vegetation cover on moist to dry ground. The very light to grey patches are areas of exposed ground with no vegetation, which may actually be salt flats where before there were lakes. The image take from 2002 shows the wedge of land between the Tigris (flowing into the scene from near top center) and the Euphrates (flowing in from near left center) reduced to a few small green patches and bare soil, varying in shades from purplish brown to pale beige. (The bright green vegetation is likely irrigated cropland, not marsh vegetation.) By 2007, a dramatic transformation had taken place in Mesopotamia. Several large marsh areas north and south of the Euphrates had been re-flooded, and the dry land south of Al Hawizeh Marsh was being systematically filled (Earth Observatory 2009).

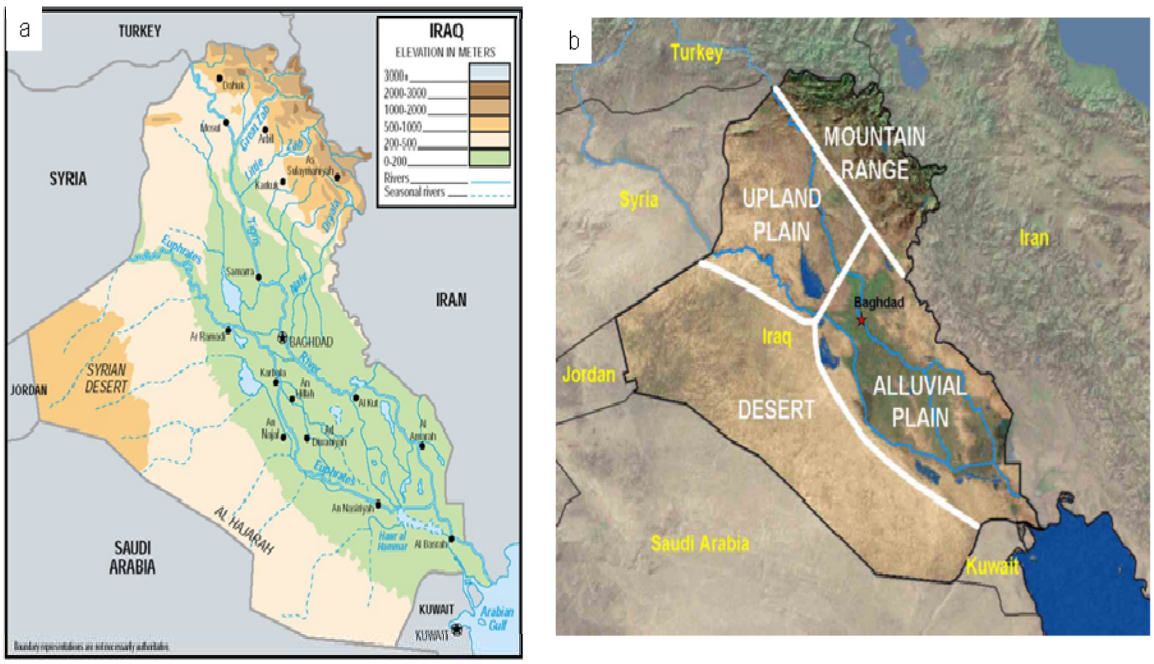

Figure 4. Topography and major geographic provinces of Iraq: (a) elevation and (b) desert, alluvial plains, and mountain regions of Iraq (14th WS 2009)

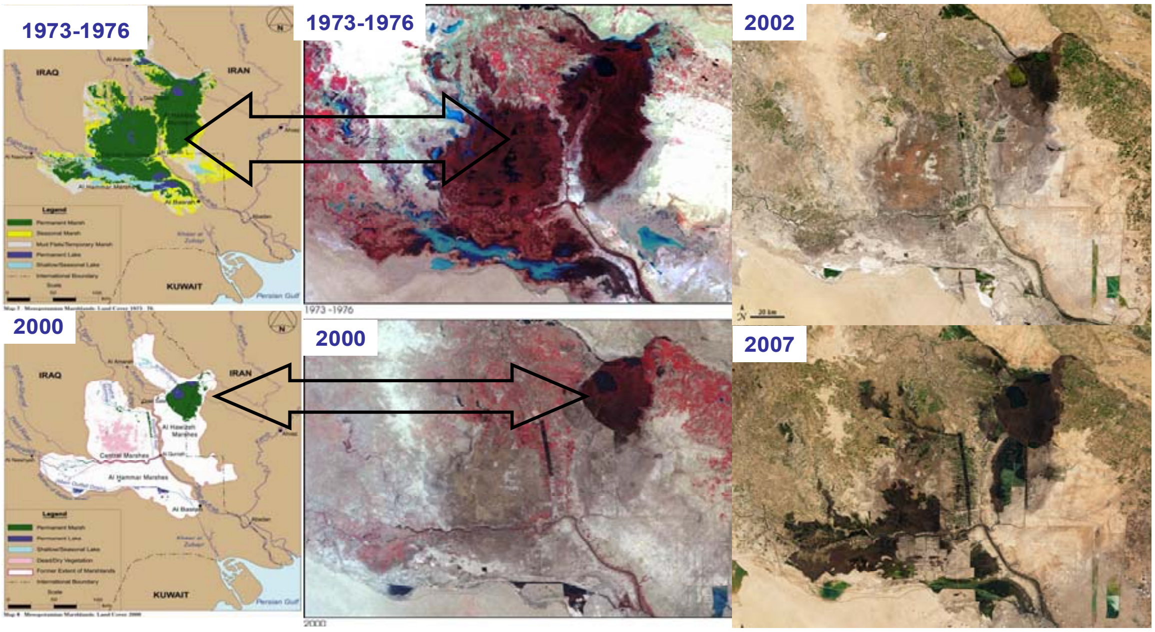

Figure 5. Maps and satellite imagery of the alluvial plains region of Iraq between the Tigris and Euphrates rivers, which formed extensive marshlands prior to a reduction of inflow and precipitation, and human draining that began in the 1990s. Human efforts to restore the marshes began in the 2000s and the resulting increase in marshland is evident in the 2007 image. The image from 1973-1976 is a false-color composite made from data collected by the Multi-Spectral Scanner (MSS) aboard Landsat from 1973-76. Four Landsat scenes were stitched together to make an image of the whole region. The bottom left image is a false-color composite of data from the Landsat 7 Enhanced Thematic Mapper Plus (ETM+), acquired on March 26 and May 4, 2000. The images from 2002 and 2007 are from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite (Earth Observatory 2009). See text for more details.

The primary soil types in Iraq are silt and clay (Figure 6), with fine and very fine particles (< 0.07 mm in diameter) that are relatively easily lifted and transported by the wind. Because there is little vegetation in much of Iraq, these particles are relatively exposed to the wind and susceptible to becoming airborne (Warner 2004; COMET 2005). This makes Iraq prone to dust storms.

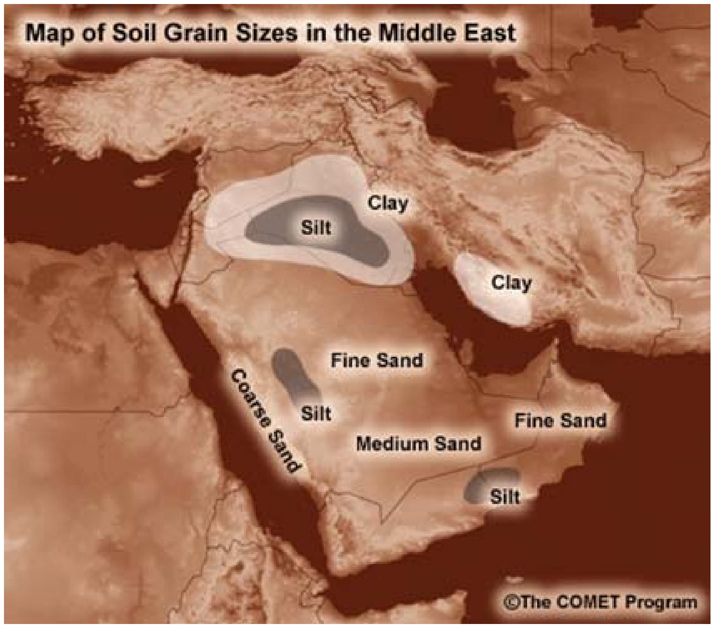

Figure 6. Soil grain types in the Middle East. Note that the majority of Iraq is comprised of silt and clay, which are fine particles (COMET 2003).

C. LONG TERM MEAN (LTM) CLIMATOLOGY OF IRAQ

Generally, cooler surface air temperatures occur in the winter and fall months, with the warmest temperatures in the summer months. The LTM precipitation rate (PR) is generally higher in the winter and fall months, and zero or very little precipitation occurs in the summer months. Figure 7 shows the average monthly precipitation and days of precipitation for various stations in Iraq. The seasonal cycle of precipitation is similar throughout Iraq, with highest precipitation during the winter months, little or no precipitation in the summer, and intermediate amounts in the spring and fall.

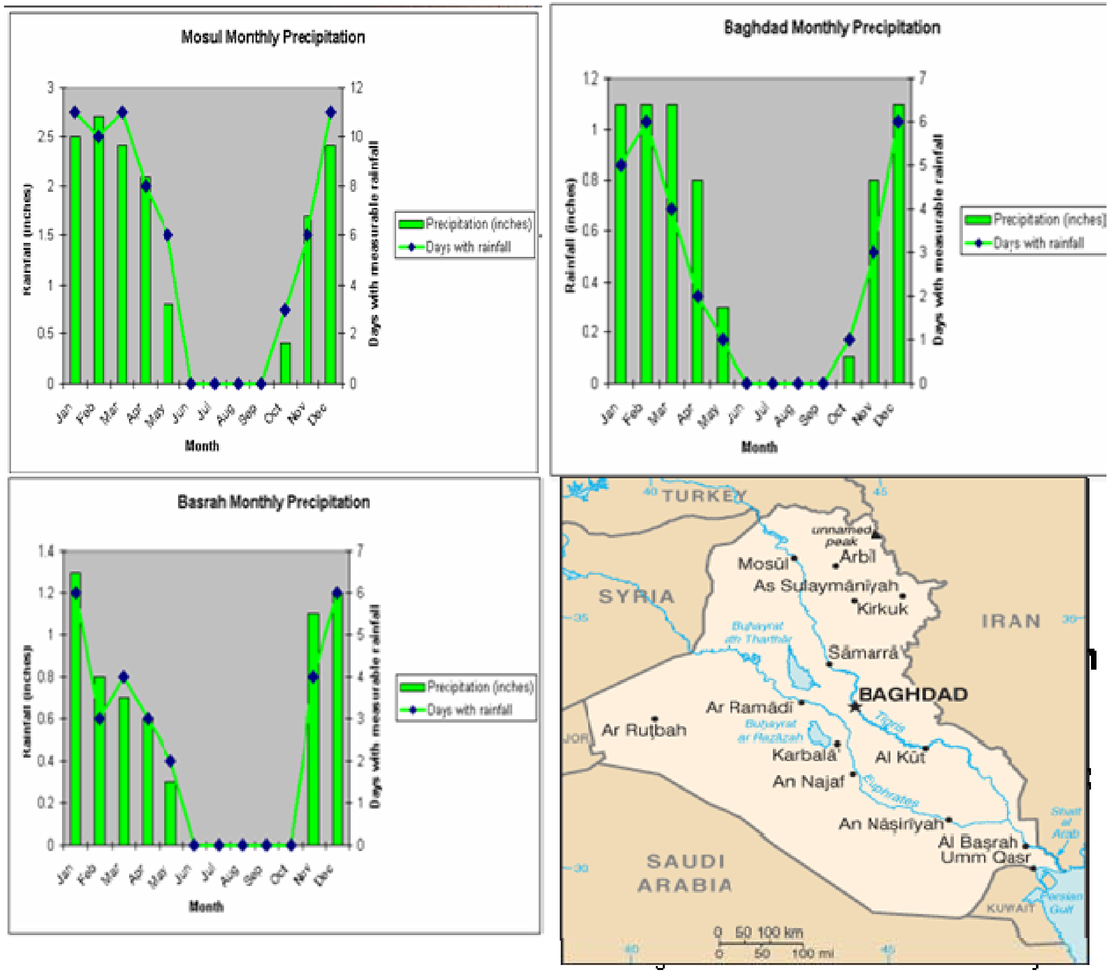

Figure 7. Monthly precipitation (green bars) and number of precipitation days (blue diamonds) for various locations in Iraq. The data used for these are from the Operational Climate Data Summary (OCDS) at 14th WS. Graphics from Iraq Yearly Study – 14th WS and CIA Fact Book.

Figure 8 illustrates the primary and secondary storm tracks that affect Iraq. The tracks indicate regular storm passage during the winter and spring seasons, while during the summer months, the storm tracks are to the north of Iraq.

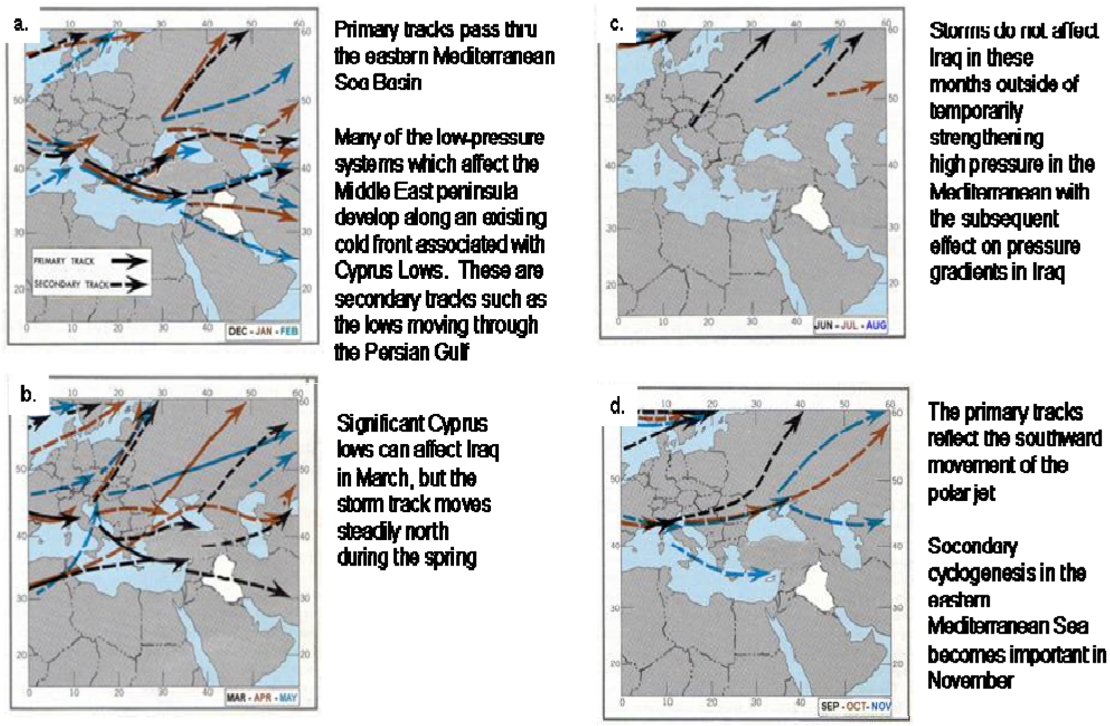

Figure 8. Primary storm tracks affecting Iraq during: (a) December–February; (b) March–May; (c) June–August; and (d) September–November. Figure from 14th WS (2005)

1. Seasonal Cycle

In winter (January–March), a main driver of Iraq climate is the semi-permanent Asian High from which cold dry air often extends westward into Iraq (Hanson 2007; Wilkerson 1991). The polar front jet (PFJ) extends the farthest south during the winter season and can merge with the subtropical jet (STJ) near Iraq and enhance the development of midlatitude cyclones over Iraq. Dust storms that occur during winter tend to be associated with both southeasterly winds ahead of synoptic low pressure systems and northwesterly winds after the passage of cold fronts. The latter winds are often referred to as the winter shamal and are discussed further in Section E.2.

In the spring (April–June), Iraq transitions out of winter conditions and towards the thermal trough conditions of summer. Midlatitude cyclones are common in the early part spring but much less common by the end of spring.

In the summer (July–September), Iraq lies under a thermal trough that extends northwestward from Pakistan and is associated with the Asian summer monsoon. Lower level ridging over the Mediterranean Sea combined with the thermal low over Pakistan result in a tendency for northwesterly winds over Iraq, referred to as the dry shamal. The winds average 10–15 knots, but there can be periods of several hours to several days in which the winds reach 25 knots. When these sustained winds occur, it is common to see gusts of 40–50 knots (NCDC 2009). Diurnal wind variations are common in much of Iraq, with winds tending to be strongest (weakest) in the afternoon (at night) (NCDC 2009).

In fall (October–December), the transition back to winter conditions begins. The winds remain northwesterly but weaken, decreasing to an average of five to ten knots. Precipitation, primarily in the form of rain showers, resumes beginning in October and gradually increases through the winter (NCDC 2009).

D. GLOBAL SCALE CLIMATE VARIATIONS

There have been several studies detailing the impacts of global scale climate variations—such as El Nino/La Nina (ENLN), the Indian Ocean Zonal Mode (IOZM), the Madden-Julian Oscillation (MJO) and the North Atlantic Oscillation (NAO)—on southwest Asia (e.g., Barlow et al., 2005; Vorhees 2006). Thus, these variations need to be considered when conducting climate analyses and long range forecasting of dust storms in Southwest Asia.

1. El Nino / La Nina (ENLN)

El Nino/La Nina (ENLN) is a climate variation centered in the tropical Pacific atmosphere and ocean that can have far-reaching effects. In particular, ENLN has been linked to variations in surface temperature, winds, and precipitation in Iraq and other parts of southwest Asia (Vorhees 2006; Hanson

2007; Moss 2007). Figure 9 shows one process by which ENLN can influence Southwest Asia by initiating quasi-stationary Rossby waves that alter the circulation and temperature and moisture advection into Southwest Asia. In particular, anomalous convection over the maritime continent (MC) associated with ENLN triggers a circulation anomaly, which in turn causes climate variations in Southwest Asia.

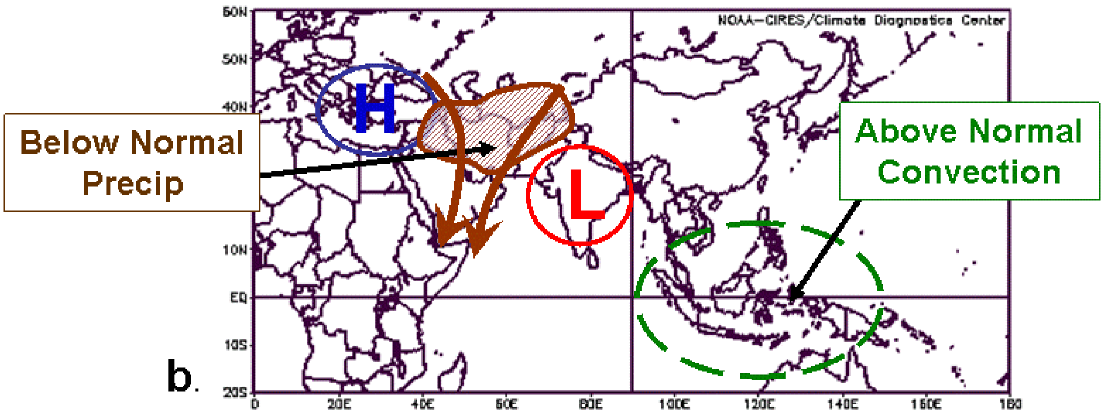

Figure 9. A schematic depiction of how above normal convection over the maritime continent influences the precipitation rate in Southwest Asia. The opposite result occurs when there is below normal convection over the maritime continent. From Vorhees (2006).

Very little research exists as to whether climate variations affect the formation of dust storms in Southwest Asia. However, such effects seem plausible given the influence of ENLN on precipitation and winds in Southwest Asia (e.g., Vorhees 2006).

2. Madden-Julian Oscillation (MJO)

The Madden-Julian Oscillation (MJO) is a global scale atmosphere-ocean variation centered in and propagating eastward through the tropics. It involves intraseasonal (30–60 day) variations in winds, upper ocean temperature, precipitation, and other variables. Vorhees (2006) and Stepanek (2006)

demonstrated that MJO can initiate climate variations in Southwest Asia via mechanisms similar to those by which ENLN influence Southwest Asia (see, for example, Figure 9).

3. North Atlantic Oscillation (NAO)

The North Atlantic Oscillation (NAO) involves large-scale variations in atmospheric mass between the subtropical and subpolar northern hemisphere and is centered in the North Atlantic (Bridgman and Oliver 2006). The positive phase of the NAO brings more storms to northern Europe, while southern Europe and the Middle East are drier than normal. The negative phase of the NAO brings more storms and precipitation to southern Europe and the Middle East while northern Europe is drier (Vorhees 2006).

4. Indian Ocean Zonal Mode (IOZM)

The Indian Ocean Zonal Mode (IOZM) is an interannual variation of the atmosphere and ocean in the tropical Indian Ocean region. The positive phase of the IOPZ is characterized by anomalously low (high) SSTs and low (high) convection in the eastern (western) tropical Indian Ocean, and anomalous easterly (westerly) low level winds over the tropical Indian Ocean (Vorhees 2006; Twigg 2007). Vorhees (2006) showed that the positive phase of IOZM tends to produce positive (negative) precipitation anomalies in Southwest Asia in the fall (winter). The mechanism for these impacts on Southwest Asia are similar to those for ENLN (see for example Figure 9).

E. GENERAL CHARACTERISTICS OF DUST STORMS

1. Dust Sources and Transport

Dust source regions are located within Iraq as well as in the surrounding countries, particularly to the north and northwest of Iraq (Figure 10). Note that most of the sources are in the upland plains region and the alluvial plains of Iraq,

including the portion of the alluvial plains formerly occupied by marshlands (see Figures 4 and 5). This indicates that winds from the northwest may be especially effective in producing dust storms over Iraq.

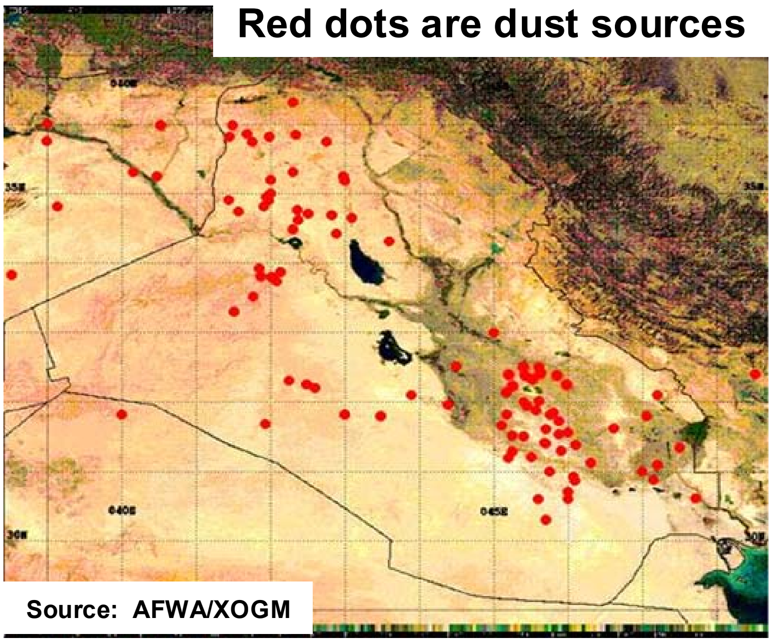

Figure 10. Source regions of dust in Iraq as well as in the surrounding regions. From 14th WS 2005

Warner (2004) describes three major processes by which winds transport dust:

a. Creep: movement of particles along the ground by rolling and sliding
b. Saltation: movement of particles through a series of jumps or skips
c. Suspension: lofting of particles by winds, especially turbulent winds

All of these processes are enhanced by strong persistent winds that extend well upward from the surface, and by the presence of dry and fine sized particles (silt and clay size) (Warner 2004).

Thus, Iraq may be especially susceptible to dust storms when strong persistent winds occur after a period in which precipitation has been low. This

situation could occur in, for example, in winter, if precipitation in the Iraq region has recently been low, and if ridging over the Mediterranean is strong and the Asian High is weak.

2. Types of Dust Storms

The types of dust storms occurring in Iraq vary by seasonal and region. Iraq's main types of dust storms are shamals and frontal passage dust storms.

a. Shamals and Frontal Dust Storms

Shamal is the local term for northwesterly winds associated with dust. There are two types of shamals; winter and summer (Wilkerson 1991). Winds travel from northern to southern Iraq, picking up much of their dust load from source areas near the Tigris and Euphrates Rivers (e.g., alluvial plains and dried marshlands shown in Figures 4 and 5). In winter, a large number of shamals occur in as part of the northwesterly flow that tends to occur after the passage of cold fronts (Walker 2002).

Dust storms during the passage of midlatitude fronts can be enhanced if the associated PFJ and STJ converge into a single jet maximum. The overlapping of these jets and the coupling of secondary circulations enhance upward motions and increase the lifting force for blowing dust. The winds associated with pre-frontal (post-frontal) dust storms are mostly southerly or southeasterly (northerly or northwesterly). Frontal dust storms tend to last as long as the frontal winds are present, which can mean up to three to five days if the front stalls and becomes stationary. The severe dust storm that occurred soon after the start of OIF in late March 2003 is an example of dust storm related to frontal passage (Hinz 2004; Anderson 2004; Liu et al., 2007).

In summer, shamals can occur when there is an intersection of (a) the eastern side of the subtropical ridge over North Africa and the Mediterranean Sea (b) the thermal low over Southwest Asia. This intersection creates strong northwesterly winds along the intersection that can create large dust storms that

flow from northern Iraq to Kuwait and the Arabian Gulf. For both winter and summer shamals, the northwest to southeast orientation of the Zagros Mountains in northeastern Iraq and western Iran (Figure 4) tends to confine and accelerate the northwesterly flow through Iraq.

3. Favorable Pre-Conditions for Dust Storm Formation

Table 1 lists factors favorable for dust storm formation. These factors were developed for use in short range forecasting of dust storms in Iraq. Several of these factors may also be useful in long range forecasting of dust storms. For example, the potential for long range forecasting of winds, midlatitude cyclone activity, precipitation shown by Vorhees (2006), Hanson (2007), and Moss (2007) indicate that several of the factors listed in Table 1 may be predictable at leads times of several weeks to several months.

Parameter or Condition for Dust Generation	**Favorable for Dust Generation When**
Location with respect to source region	Located downstream and in close proximity
Agricultural practices	Soil left unprotected
Previous dry years	Plant cover reduced
Wind speed	$\geq$ 15.4 m s^{-1}
Wind direction	Southwest through northwest (dust source upstream)
Cold front	Passes through the area
Squall line	Passes through the area
Leeside trough	Deepening with increasing winds
Thunderstorm	Mature storm in local area or generates blowing dust upstream
Whirlwind (dust devil)	In local area
Time of day	1200 to 1900 L
Surface dewpoint point depression	$\geq$ 10° C
Parameter or Condition for Potential Dust Advection	**Favorable for Dust Advection When**
Wind speed	$\geq$ 5.1 m s^{-1}
Wind direction	Along trajectory of the generated dust
Synoptic situation	Ensures the wind trajectory continues to advect the dust

Table 1. Conditions found to be favorable for the generation and transporting of dust. From Bartlett (2004).

Table 2 is a consolidated list of factors contributing to dust storms based on our synthesis of prior studies and personal communications with subject matter experts.

Factors Favorable for Dust Storms that are Potentially Predictable at Long Lead Times
Wind at low levels (high speeds, direction that favors high speeds and turbulence, occurrence over and direction away from dust sources)
Low precipitation
Low relative humidity
Low soil moisture
High temperature at surface and low levels
Turbulence at low levels
Little vegetation covering land surface
Human disruption of land surface

Table 2. Factors that contribute to the generation of dust storms that may be predictable at lead times of several weeks or longer.

Prior studies indicate that all of these factors may be known or predictable at long lead times (see section D, Chapter I). For example, wind and precipitation variations in Iraq have been linked to remote global scale climate variations occurring several weeks or months earlier. Thus, the factors in Table 2 may be suitable predictands for long range forecasting. Note that these factors are not all independent of each other. For example, low precipitation, low relative humidity, and low soil moisture tend to be well correlated. Therefore, long range prediction of just some of these factors may account for most of the factors and thus be sufficient for producing skillful long range forecasts of the potential for dust storms.

For this study, we focused on developing a system for long range forecasting of Iraq precipitation and winds, and thus, for long range forecasting of the potential for dust storms in Iraq. We chose precipitation and winds as our predictands because: (1) prior studies have shown they may be predictable at

long lead times when using global scale climate variations as predictors; and (2) precipitation and wind variations are closely associated with several other dust favorable factors, including air temperature, turbulence, relative humidity, soil moisture, and vegetation .

F. DUST FORECASTING MODELS

The Department of Defense (DoD) has three main models that are used in short range (lead times of 0–5 days) forecasting of dust storms. These models are summarized in the following three sub-sections and in Table 3.

Dust Model	COAMPS	NAAPS	AFWA CARMA
Model dimensions	Horiz. res. 9 km, 46 layers to 32km	1-degree horiz. res., 24 levels up to 100 mb	100 km horiz. res., 21 levels
Model domains	SW Asia, East Asia	Global	SW and East Asia, Med.
Meteorology	COAMPS at each timestep and grid point	NOGAPS, 6-hourly	MM5: 41 levels, 45-km horiz. res., 3-hourly
Forecast Length	72 hours	5 days	72 hours
Dust Source	Walker (1km) and USGS,TOMS AI	USGS, TOMS AI, Obs.	Topo., TOMS AI
Forcing	u_*^4 (Nickling and Gillies 1993)	u_*^4 (Westphal et al., 1987, 1988)	10-m wind (Ginoux et al. 2001)
Sizes (diam.)	0.05 to 36 um	2 um	1 to 20 um
Bins	10 (1 for operations)	1	10
Size dist.	bimodal lognormal, sandblasting model (Alfaro et al. 1997)	None	Ginoux (et al., 2001)

Table 3. Comparison of dust forecasting models used within DoD. From Westphal, Walker, and Liu (2004).

1. Coupled Oceanographic and Atmospheric Mesoscale Prediction System (COAMPS)

The Coupled Oceanographic and Atmospheric Mesoscale Prediction Model (COAMPS) is a rapidly relocatable non-hydrostatic model that includes an optional predictive, first principles-based aerosol modeling capability (Liu et al., 2003). The model forecasts are available at up to 72 hours lead time with output

at three hour intervals. A triply nested (81 km–27 km–9 km) set of model domains with the embedded dust option turned on is routinely run for Southwest Asia, with the domains centered on Iraq. A 1 km dust source database for the region was derived from Total Ozone Mapping System (TOMS) data as well as the USGS Land User Characteristics Database. The COAMPS dust model produces three-day forecasts of aerosol mass concentration, aerosol mass load, extinction coefficient, and optical depth (NRL, Accessed: May 2009; Bartlett, 2004).

2. Navy Aerosol Analysis and Prediction System (NAAPS)

The Navy Aerosol Analysis and Prediction System (NAAPS) was developed at the Naval Research Laboratory Marine Meteorology Division. It draws from the Navy Operational Global Atmospheric Prediction System (NOGAPS) global model and forecasts dust storms up to 120 hours in advance. The model uses global meteorological analyses and forecasts on a 1 X 1 degree grid, at 6-hour intervals and 24 vertical levels from the surface to 100 hPa. The strengths of the model are: its use of operational dynamics, 120-hour forecast lead time, availability in near real-time, global coverage, and ability to simulate both dust and smoke. The dust source areas for the model are identified based on the USGS Land Cover Characteristics Database. The dust algorithm calculates dust fluxes from the surface into the lower two layers of the model (Westphal 1988).

3. Dust Transport Application (DTA)

The Dust Transport Application (DTA) is the dust model primarily used by the United States Air Force (USAF). Developed by the Johns Hopkins University Applied Physics Laboratory, it uses a global dust source database developed by Dr. Paul Ginoux, affiliated with National Ocean and Atmospheric Association/Coastal Fluid Dynamics Lab (NOAA/CFDL), and an aerosol transport model based on the Community Aerosol Research Model for Atmospheres

(CARMA). The model assimilates weather data from any of several standard meteorological models, such as MM5 and WRF ARW. The output is a 72-hour forecast of dust aerosol concentrations, visibility, and dust loading. The model calculates the amount of surface dust flux at each grid location, and includes routines to calculate lofting, transport, and deposition of dust. The dust source database is based on surface topography and persistent dust signatures observed by satellite-borne sensors (JHU/APL March 2009).

G. LONG RANGE FORECASTS CURRENTLY USED OR AVAILABLE

There are presently no systems available for long range forecasting of dust storms (lead times of two weeks or longer). However, the ability to forecast dust storms at long lead times would be very useful in mitigating the adverse impacts they have on military operations. Long-range forecasts could be used at the operational level to better prepare for the risks and opportunities presented by dust storms.

1. Long Range Forecasts from Department of Defense (DoD)

Currently, the 14th Weather Squadron (14th WS) is the only DoD center for the production center of long range forecasts**.** The 14th WS produces 30–90 day forecasts for air temperature, precipitation, and ceilings for Iraq and Afghanistan. For example, in March, they issue long range products for April, May, and June via their website: https://notus2.afccc.af.mil/SCISPublic/. Their products identify regions in Iraq and Afghanistan where the predictands (e.g., precipitation rate) are above normal, near normal, or below normal. These forecasts are based primarily on current and projected ENLN conditions. They also take into account long range forecasts from civilian agencies, such as European Center for Medium-Range Weather Forecasting (ECMWF) and Climate Prediction Center (CPC). The 14th WS and other DoD organizations (e.g., Fleet Numerical Meteorology and Oceanography Center, Naval Oceanographic Office) also provide long range support products that are summaries or analyses of past

conditions and not true forecasts. Many of these products are based on less than optimal input data sets and analysis methods. They tend to emphasize long term mean conditions, and offer little or no guidance on climate variations, trends, and other deviations from long term mean conditions. They also tend to be deterministic products rather than probabilistic products (e.g., they describe the long term mean conditions rather than the probability of the long term mean conditions occurring).

2. Civilian Long Range Forecasts

Several civilian agencies produce long range forecasts for various regions for a variety of applications (e.g., precipitation forecasts to determine the probability of flooding conditions). These products generally have lead times of several weeks to several seasons and have valid periods of one month to one season. The Climate Prediction Center (CPC) uses several tools for its season/monthly outlooks, including a coupled ocean-atmosphere ensemble forecast (CFS), ENLN composites, and correlation analysis. Most CPC forecasts are focused on the U.S. and nearby regions. More information regarding these tools can be found at:
http://www.cpc.noaa.gov/products/predictions/long_range/tools.html.

The International Research Institute for Climate and Society (IRI) produces monthly and seasonal forecasts of SST, precipitation, and temperature for most of the globe, including Southwest Asia. For more information, we refer the reader to their website: http://portal.iri.columbia.edu/portal/server.pt.

Other agencies also produce monthly and seasonal forecasts (e.g., ECMWF, United Kingdom Meteorological Office, and Australian Bureau of Meteorology). Their products are similar in method and scope to those of CPC and IRI. None of these organizations, however, produces long range forecasts focused on the potential for dust storms.

H. MOTIVATION

Previous research has shown that the global scale climate variations affect Iraq and other areas of DoD interest. Specifically, many of these studies have demonstrated that climate variations (e.g., ENLN, MJO, IOZM) can alter the winds and precipitation in Southwest Asia in predictable ways (e.g., Vorhees 2006; Hanson 2007; Moss 2007). This predictability is due in large part to the persistence, or low frequency character, of the climate variations. Thus, once these variations are initiated, they and their impacts tend to persist for several weeks or months. These prior studies were a primary motivation for our study. We were also motivated by the absence of any systems for long range forecasting of dust storms, and clear evidence of the need for such forecasts for DoD planning. In spring 2008, the 14th Weather Squadron requested our assistance in investigating the causes of an extremely high number of dust storm days in Iraq during spring 2008.

Our initial investigations of these conditions led us to the main hypothesis which we tested in this study (see Figure 11): (1) remote climate variations initiate circulation anomalies in Southwest Asia and nearby regions; (2) these anomalies lead to precipitation and wind anomalies in Iraq that are favorable for the formation of dust storms. To test this hypothesis, we needed to identify the Iraq precipitation and wind anomalies associated with Iraq dust storms. We then needed to identify the regional and global scale conditions prior to and during these precipitation and wind anomalies. We then needed to use this information on the characteristic local, regional, and global conditions prior to and during dust storms to develop methods for predicting dust favorable conditions and the potential for dust storms. Chapter II describes our data sets and methods, chapter II describes our results, and Chapter IV makes recommendations on future research and operational applications of our research.

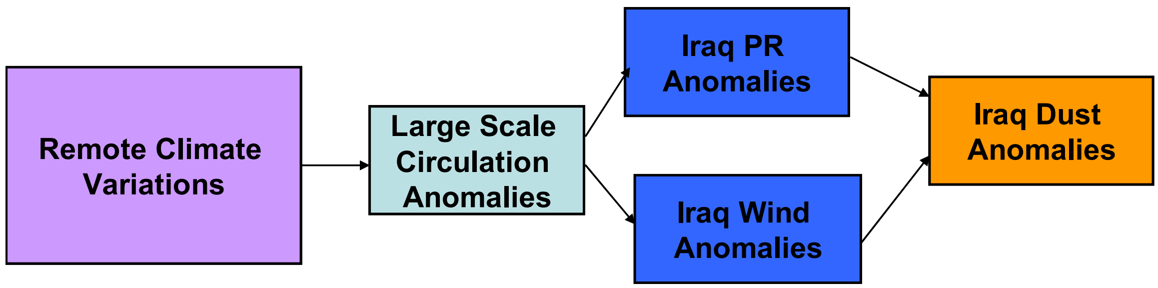

Figure 11. Flow chart of the climate scale processes we hypothesized lead to favorable conditions for dust storms in Iraq. We tested this hypothesis in this study. .

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II. DATA AND METHODS

A. DATA

1. Climate System Data

The primary data set we used for this study is the National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) reanalysis data set. NCEP and NCAR joined in producing a 40-year global reanalysis of atmospheric fields (Kalnay et al., 1996). The reanalysis analyzes data from various sources, including land surface, ship, rawinsonde, aircraft, and satellite observations. The reanalysis spans 1948 to the present and helps to fulfill the needs of the climate research community for comprehensive and temporally extensive data on the climate system (Kalnay et al. 1996; Kistler et al., 2001). We used this data set to analyze characteristic conditions prior to and during dust storms in Iraq, including potential predictors and predictands of dust storms (see Table 2).

The primary strength of the NCEP/NCAR reanalysis is its ability to describe monsoons, droughts, and other low frequency climate variations. It is available at a temporal resolution of six hours on a uniform horizontal grid with spatial resolution of 2.5^{o} and at all standard tropospheric and stratospheric levels from January 1948–present. In this study, we used data from January 1970 to March 2009. Previous studies have shown that the NCEP/NCAR reanalysis data is sufficiently accurate to meet the requirements for this research (e.g., Vorhees 2006). The reanalysis data is especially useful for data sparse regions, such as Southwest Asia and ocean regions.

The reanalysis fields are classified into four groups according to the relative influence of the observational data and the model used to analyze the observational data. Kalnay et al. (1996) describe the categories of the variables—A, B, C, and D—as follows:

An A indicates that the analysis variable is strongly influenced by observed data, and hence it is in the most reliable class (e.g., upper-air temperature and wind). The designation B indicates that, although there are observational data that directly affect the value of the variable, the model also has a very strong influence on the analysis value (e.g., humidity and surface temperature). The letter C indicates that there are no observations directly affecting the variable so that it is derived solely from the model fields forced by the data assimilation to remain close to the atmosphere (e.g., clouds, precipitation, and surface fluxes). Finally, the letter D represents a field that is obtained from climatological values and does not depend on the model (e.g., plant resistance, land-sea mask).

Although there are weaknesses in this reanalysis data set, the advantages, availability, and fidelity clearly outweigh the disadvantages. Therefore, we used this data set as the primary resource for studying the environmental conditions occurring prior to and during the dust storm days.

2. Dust Storm Observations

To identify dust storms, we used in-situ observations at six surface stations in Iraq and two surface stations in Kuwait. The data was provided to us by the 14th WS and covered August 2003–May 2009. Figure 12 shows the locations of the stations. The station observations include data on dust-related visibility restrictions. From this data, we identified *dust storm days* as days on which dust conditions significant enough to decrease the visibility to less than one statute mile (SM) occurred at: (1) five or more of the eight stations in Iraq and Kuwait; or (2) three or more of the Iraq stations and one or more of the Kuwait stations. In some instances, two or more consecutive dust storm days occurred. We refer to these instances as *dust storm events*.

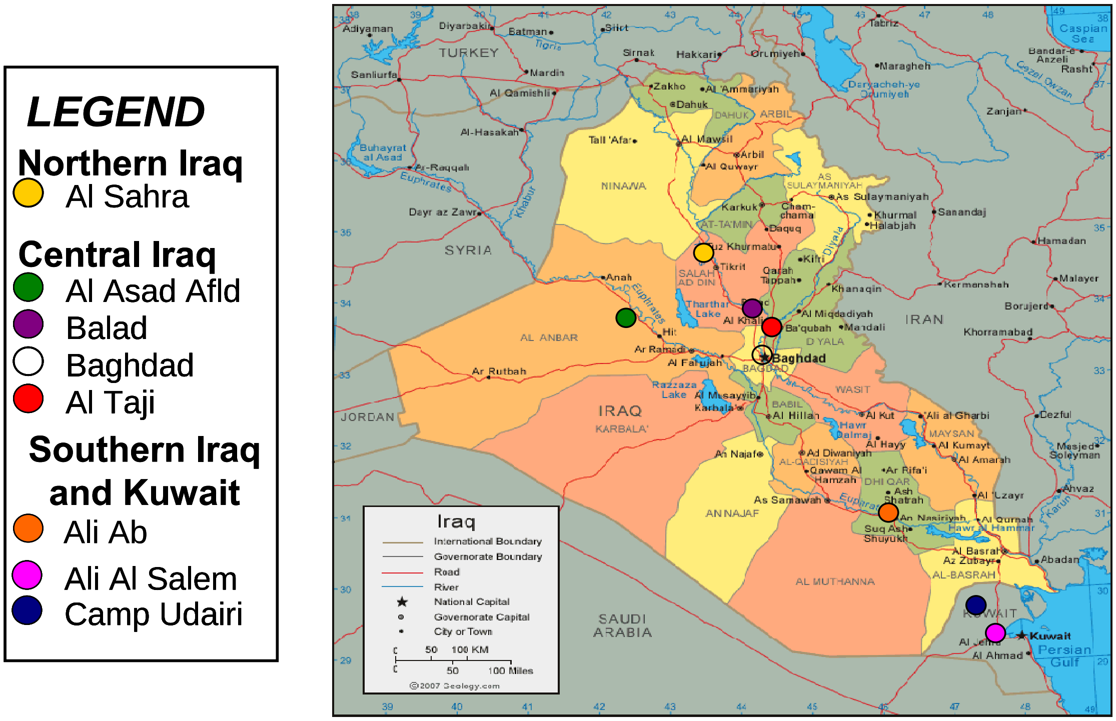

Figure 12. Surface observation stations for which data on dust storm activity was available from the 14th WS. Base map from: http://geology.com/world/iraq-map.gif.

The primary strength of this data set is that it explicitly identifies days when significant dust storms occurred. The data set has daily resolution spanning six years, making it useful for studying specific cases and longer term patterns (personal correspondence from Capt Moss, 14th WS, Asheville, North Carolina May 2009). The observations appear to be more reliable and consistent in the later years. One disadvantage of this data set is that the ground stations are not evenly distributed throughout Iraq, with the majority near Baghdad and no stations in western Iraq.

To verify the dust storm days identified from the 14th WS data, and to identify additional dust storm days, we examined satellite imagery and other remote sensing techniques. Using images from the Earth Observatory website (http://earthobservatory.nasa.gov/), we were able to confirm many of the dust

storm days and to add several more days not recorded in the 14th WS data, especially for 2003. Dust detection algorithms enhanced the satellite imagery available at this site, making the dust readily apparent.

B. METHODS

1. Conditional Composites

Using the NCEP/NCAR reanalysis data, we created conditional composites for dust storm days (e.g., mean sea level pressure (SLP) during dust storm days in January-March of 2003–2008; mean precipitation rate during the 30 days prior to dust storm days in January-March of 2003–2008). We compared these conditional means to the corresponding long term means (e.g., the mean SLP for all days, not just dust storm days) and corresponding anomalies (e.g., the mean SLP for all dust storm days minus the long term mean SLP) (Murphree 2008). We created these composites for a wide range of variables, but with a focus on precipitation rate and low level winds as inferred from sea level pressure gradients (see Table 2). The conditional composites, long term means, and anomalies were constructed for the southwest Asia region to identify characteristic conditions prior to and during dust storm days on regional and global scales. Most of our conditional composites were for individual months, seasons, and groupings of seasons (e.g., a fall-winter grouping, October-March).

2. Time Series

We also used the reanalysis data set to construct annual, seasonal, and monthly mean time series for 1970–2008 of precipitation, SLP, SST, and other variables. The time series were constructed for area averaged quantities (e.g., the average precipitation rate for all reanalysis grid points within the Iraq region). Figure 13 shows the seasonal cycle of precipitation rate (PR) in Iraq for various

averaging periods. We used similar time series of other variables to study seasonal and yearly patterns, for calculating correlations between variables, and for use in developing and testing our long range forecasting methods.

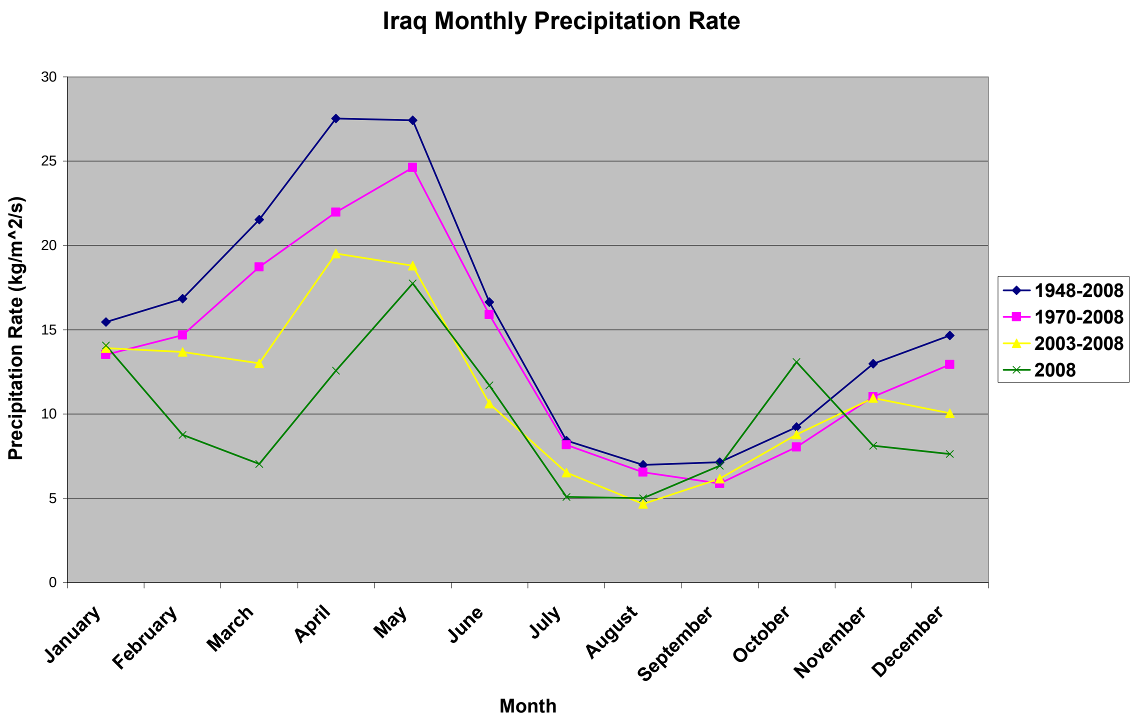

Figure 13. The monthly mean precipitation rate (PR) time series for Iraq for: 1948-2008 (blue); 1970–2008 (red); 2003–2008 (yellow); and 2008 (green). Note the lower PR in recent years compared to the longer term means, especially in winter and spring.

3. Correlations and Teleconnections

The time series were used to calculate correlations between variables, especially lag relationships between variables at widely separated locations (e.g., between SST in the Indian Ocean and SLP over the Mediterranean Sea). Significant long distance correlations were used to identify teleconnections. Our correlations were calculated from monthly means for 1970–2008. Correlations greater than +/- 0.314 were statistically significant at the 95% confidence interval, based on the standard normal distribution of a two-tailed test (Wilks 2006).

We used lagged correlations to identify potential long lead predictors of Iraq precipitation and winds. The lags ranged from zero to three months, with the Iraq predictands (e.g., precipitation and low level winds) lagging the potential predictors (e.g., Indian Ocean SST). To represent the regional scale winds that influence dust storms in Iraq, we constructed a SLP index, calculated as the SLP anomaly over the Mediterranean-North Africa region west of Iraq (centered near Tunisia) minus the SLP anomaly over the western Asia region northeast of Iraq (centered near Kazakhstan). We used this index as a proxy for low level winds in the Iraq region. See the next section for more details on this index.

We then correlated the time series for the Iraq precipitation rate and the SLP index with the time series for SST and other climate system variables around the globe. The correlations revealed strong and significant correlations at lags of 0–2 months between the Iraq predictands (precipitation and the SLP index) and SST in the northeastern tropical Indian Ocean and in the far eastern tropical Indian Ocean between Indonesia and Australia.

4. Composite Analysis Forecast Process

These predictand-predictor relations were used to develop a long range forecasting process based on an adaptation of the Composite Analysis Forecast (CAF) process (MetEd 2009; Hanson 2007; Moss 2007). CAF process is used to generate a probabilistic long range forecast that is based on the conditional probability of a certain event occurring (e.g., the probability of below normal precipitation in Iraq in March given the occurrence of above normal SST in the eastern tropical Indian Ocean in January). Figure 14 graphically summarizes the main steps in our CAF process.

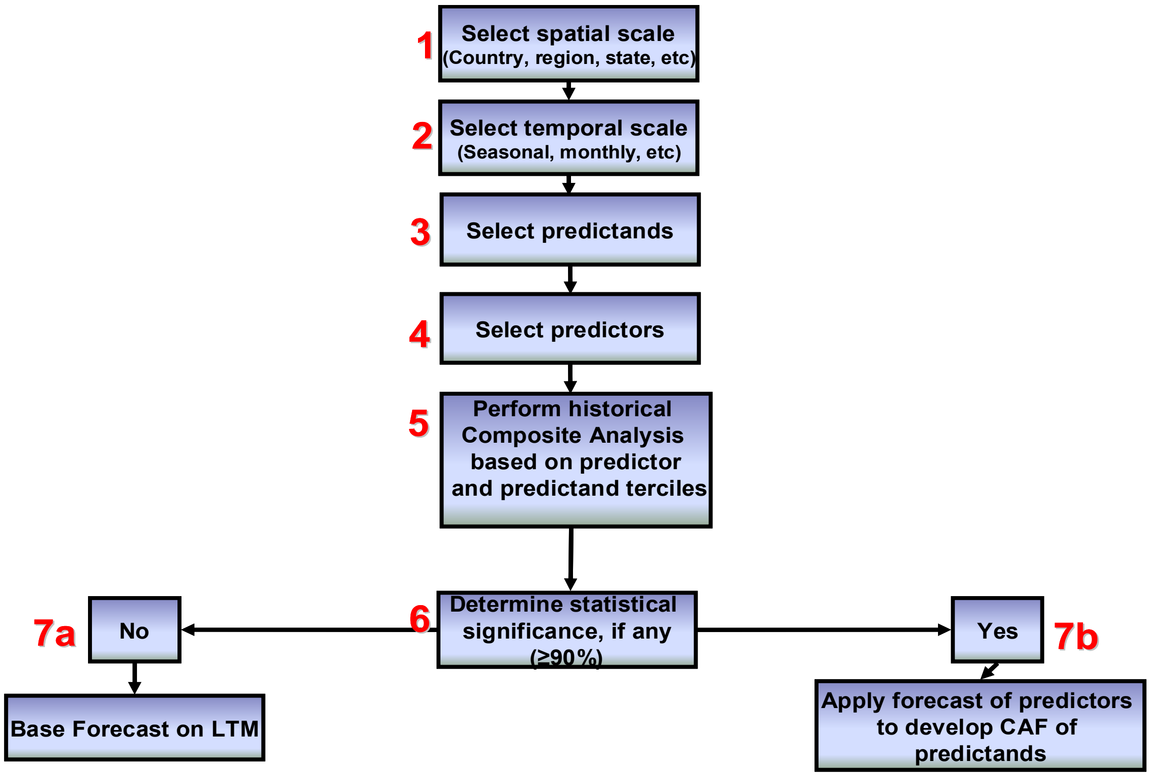

Figure 14. Flow chart outlining the CAF process for developing a long range forecast for dust storms in Iraq. Adapted from Moss (2007).

a. *Step 1 – Select Spatial Scale*

We chose Iraq for our spatial scale and region of interest, based on prior studies (Vorhees 2006, Hanson 2007, Moss 2007) and because of the DoD relevance of Iraq.

b. *Step 2 – Select Temporal Scale*

We selected a monthly scale and focused on the winter months, since winter is an active period for both dust storms and military operations (e.g., the start of Desert Storm and Operation Iraqi Freedom (OIF)).. In particular, we focused on long range forecasts for March because this month has had some large precipitation anomalies in recent years (see Figure 12) and a large number of dust storm days (see Chapter III). We used January, February, and March SST values for the predictors.

c. Step 3 – Select Predictands

The predictors we selected were PR and our low level wind proxy for Iraq, the SLP index described in the prior section. We chose PR and low level wind because previous studies have shown that these variables may be predictable at long leads based on their relationships to global scale climate variations (as discussed in Chapter I). The PR was calculated as the PR averaged over the Iraq region (29N-38N, 38E-49E). The SLP index was calculated as the area averaged SLP anomaly near Tunisia (30N-40N, 10E-20E) minus the area averaged SLP anomaly near Kazakhstan (35N-45N, 52E-62E) (see Figure 15). We named this index the Tunisia - Kazakhstan Index (TKI). We chose those regions because the SLP gradient between these two locations is an indicator of low level wind speed and direction over Iraq. Positive (negative) values of the TKI correspond to northwesterly (southeasterly) wind anomalies over the Iraq region.

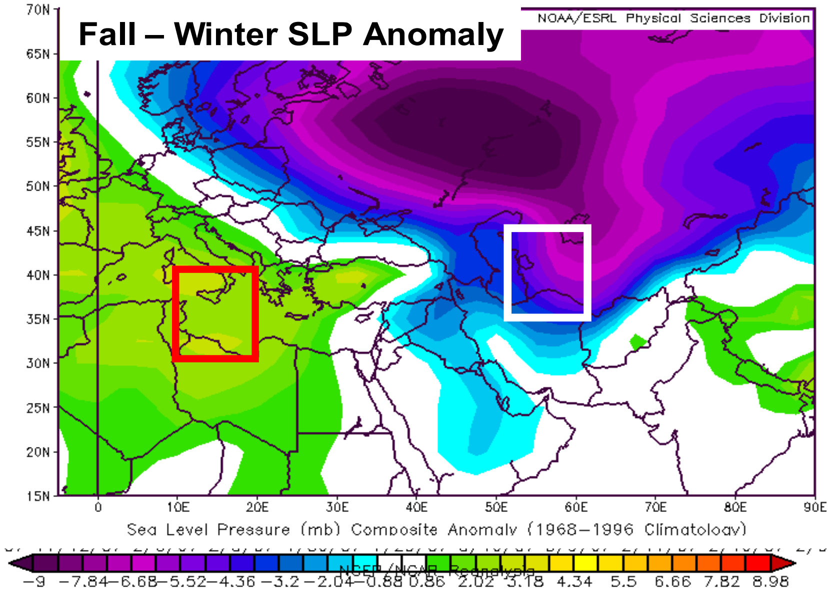

Figure 15. The October-March SLP anomaly during dust storm days in Iraq during 2003–2008 (ESRL 2009). Note the implied northwesterly wind anomalies over Iraq. The red and white boxes identify the Tunisia and Kazakhstan regions used in the calculation of the Tunisia-Kazakhstan index (TKI). See text for more details. .

d. Step 4 – Select Predictors

We experimented with using an index of ENLN conditions as a predictor, since prior studies have shown potentially predictable impacts of ENLN on Iraq winds and precipitation (e.g., Vorhees 2006; Hanson 2007), however, the correlations of Iraq PR and the TKI with Indian Ocean SSTs were stronger and more significant than with the ENLN index. Thus, we selected Indian Ocean SSTs as our predictors; in particular, SST in the northeastern tropical Indian Ocean (5S-15N, 75E-100E) and in the eastern tropical Indian Ocean between Indonesia and Australia (0N-20N, 100E-130E)

e. Step 5 – Perform Historical Composite Analysis

For step 5, we calculated the distribution of Iraq PR and TKI predictands with respect to the distributions of the two SST predictors. We

divided predictand and predictor values for 1970-2008 into above normal (AN), near normal (NN), and below normal (BN) terciles (e.g., BN PR for Iraq in March; AN SST for the far eastern IO in January). For these years, each tercile represents data from 13 years. We then calculated the distribution of the predictand values by terciles with respect to the predictor values by terciles (e.g., the number and percent of occurrences of BN PR when SST was AN or of occurrences of AN TKI when SST was AN). In our adaptation of the CAF process, our predictor is an analyzed value prior to the forecast valid time (e.g., analyzed SST in January two months prior to the March valid time). In the standard CAF process, the predictor value is a prediction of the predictor at the valid time (e.g., a prediction of March SST issued in January).

f. Step 6 – Determine Statistical Significance (>90%)

For step 6, we determined the statistical significance of the relative distributions calculated in step 5. We completed this step by performing a risk analysis using a hypergeometric distribution method. We used factors of statistical significance at a 90% confidence level (10% significance), as well as a 95% confidence level (5% significance). Thus, for example, if the number of AN, NN, or BN PR occurrences during the warm, neutral, or cool SSTs were statistically significant within those ranges (greater than 90% or 95%), using the hypergeometric distribution test, then the PR-SST relationship was considered statistically significant and very unlikely to be due to chance.

g. Step 7 – Develop the Long Range Forecast

If the step 6 results show a statistically significant relationship, then that relationship can be used to develop a long range forecast. A CAF is generated by multiplying the observed relative distribution of the predictand for each tercile category (e.g., AN, NN, or BN PR) by the corresponding category of the probabilistic forecast of the predictor (e.g., AN, NN, or BN SST). We show this calculation graphically in Figure 17. In this figure, the three equations

represent the probability of AN TKI, NN TKI, and BN TKI, respectively, given AN (warm) conditions for the SST predictor. The three right hand side terms represent the multiplication of the corresponding probabilities. For example, in the first equation, the first right hand side term represents the product of the probability of AN TKI and the probability of AN SST (warm).

$$
\begin{aligned}
P_{\text{TKI above}} &= P_{\text{TKI above / warm}} \times P_{\text{SST warm}} + P_{\text{TKI above / neutral}} \times P_{\text{SST neutral}} + P_{\text{TKI above / cool}} \times P_{\text{SST cool}} \\
P_{\text{TKI neutral}} &= P_{\text{TKI neutral / warm}} \times P_{\text{SST warm}} + P_{\text{TKI neutral / neutral}} \times P_{\text{SST neutral}} + P_{\text{TKI neutral / cool}} \times P_{\text{SST cool}} \\
P_{\text{TKI below}} &= P_{\text{TKI below / warm}} \times P_{\text{SST warm}} + P_{\text{TKI below / neutral}} \times P_{\text{SST neutral}} + P_{\text{TKI below / cool}} \times P_{\text{SST cool}}
\end{aligned}
$$

Figure 16. Equations used in the CAF Process to calculate a long range forecast of the TKI using SST as a predictor. SST warm, neutral, and cool correspond to SST AN, NN, and BN, respectively.

Notice that the calculations in Figure 16 involve all three predictand categories and all three predictor categories. However, when using analyzed predictor (e.g., SST) conditions prior to the valid time, we would use a binary “0” or “1” for the predictor probabilities, with “1” representing the probability of the actual analyzed SST condition. The resulting forecast shows the probability of AN, NN, and BN conditions occurring; the total probability sum being 100%. For example, a CAF might give a 15% probability of AN, a 30% probability of NN, and a 55% probability of BN conditions during AN SST conditions.

It is important to note that a long range forecast is constructed from the probabilities derived from each of the three equations in Figure 16, and yields a probability of AN, NN, and BN conditions for the predictand, given information about the predictor. For example, a forecast might show a 10% probability of AN PR, a 30% probability of NN PR, and a 60% probability of BN PR in March 2009 based on the SST conditions observed in January 2009. In this example, the long range forecast is weighted toward BN PR, but with a slightly less than normal probability of NN PR, and a very low probability of AN PR. It is possible for the forecast to show nearly identical probabilities (e.g., 33% probability of AN, NN, and BN PR). In this case, the chances are equal for each PR occurrence.

These probabilistic forecasts are an important step beyond the historical composite analysis results from step 6. However, the forecaster would apply the CAF method only when Steps 1-6 yielded statistically significance results in step 7 (Moss 2007; Hanson 2007). We used Microsoft Excel to generate all of the CAFs. The forecast results can be shown graphically, for example as a pie chart (see Chapter III).

If the relationships derived from step 6 do not show any statistically significant relationships, then alternate methods for estimating the predictand conditions must be used, such as the use of LTM predictand conditions (e.g., Moss 2007).

III. RESULTS

A. OVERVIEW

We examined the occurrence of dust storm days per month, per year, and per region. Overall, 181 dust storm days in Iraq during 2003-2008 met the criteria discussed in Chapter II. Figure 17 shows the distribution of yearly total PR and number of dust storm days in Iraq for 2003-2008. Note the overall downward trend in PR and the upward trend in dust storm days, with 2008 having the smallest amount of rainfall and largest number of dust storm days, and 2006 having he second highest PR and the smallest number of dust storm days. These results indicate that on a climate scale, low precipitation is a contributor to dust storms (as expected; see Table 2).

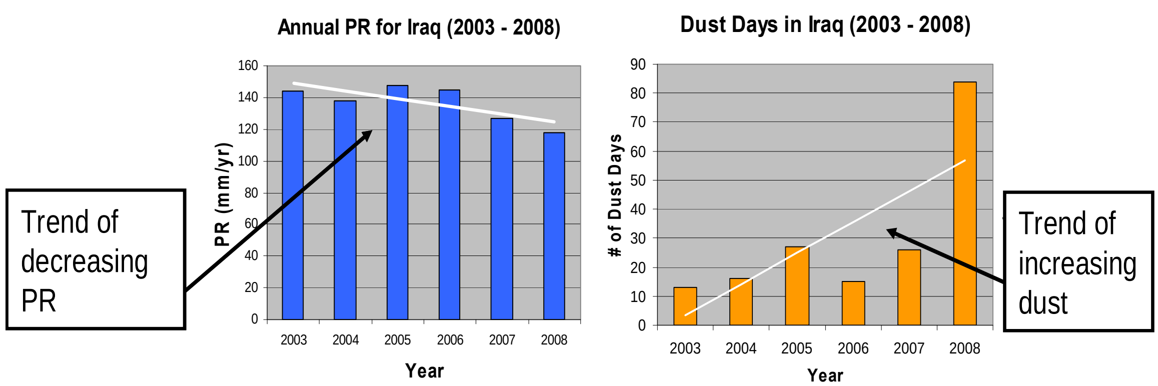

Figure 17. The annual total PR (in mm/yr; left) and number of dust storm days (right) for Iraq during 2003–2008. Note the decreasing trend in PR and increasing trend in dust storm days.

The long term mean Iraq environment (e.g., the LTM surface water in marshes and lakes, soil moisture, and vegetation covering the land surface) represents an adaptation to the LTM PR in Iraq. When the PR is persistently lower than normal, the environment (e.g., the land surface) responds in ways that make dust storms more likely (e.g., by reducing the amount of surface water, soil moisture, and vegetation). These responses may occur slowly or rapidly (e.g., slow loss of marshes over several years or the rapid loss of soil moisture over

several months). The slower responses may help explain the large increase in the number of dust storm days from 2007 to 2008, even though the decrease in PR from 2007 to 2008 was relatively small (see Figure 17). In addition, if relatively low PR occurs in the late winter and spring when low level winds tend to be strong and when annual vegetation (e.g., wild grasses, cereal crops) tends to be established, then the effects of the PR decrease on dust storm activity may be especially strong. This sort of PR timing effect may help to explain the interannual variations in dust storm days. For example, the effects of low precipitation in the late winter and spring may help explain the large number of dust storm days in spring and summer 2008, which occurred after exceptionally low PR in February–April 2008 (see Figure 13). Timing effects may also help explain the counter intuitive relationships between PR and dust storm days, shown in Figure 17; for example, in 2005, when a relatively large number of dust storm days occurred despite relatively high PR.

Figure 18 (left panel) shows that the downward trend in PR seen in Figure 17 is part of a longer term trend that can be traced back to at least the mid-1990s. Figure 18 (right panel) shows that the low PR during 2003-2008 is largely the result of a decrease in late winter and spring precipitation compared to the 1970-2008 LTM PR (Figure 18, right panel).

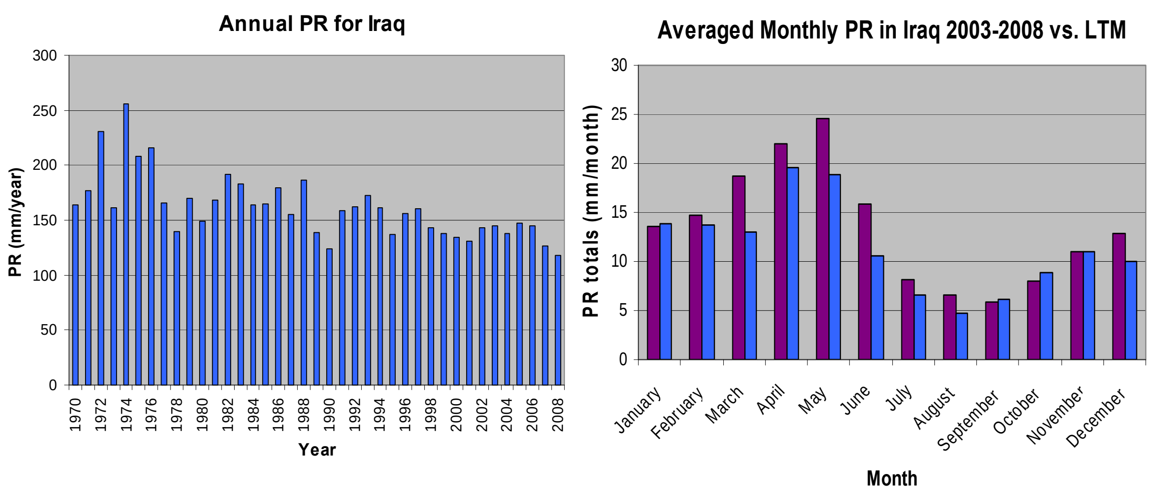

Figure 18. Annual total PR for Iraq (left) and monthly total PR for Iraq during 2003–2008 and 1970–2008 (in mm/yr).

Figure 19 shows the monthly PR and the monthly number of days of dust in Iraq during 2003–2008. The winter-spring (summer) had the highest (lowest) PR, while the spring (fall) had the highest (lowest) number of dust storm days. Although the highest PR during 2003–2008 occurred during the spring, the late winter and spring PR was below normal (see Figure 18) and coincided with the largest number of dust days. This suggests that low PR in the late winter and spring may be especially likely to lead to dust storms in the spring. This also suggests that long range forecasts of spring dust storm activity may be based on PR in the prior month or months, and to the factors that determine prior PR.

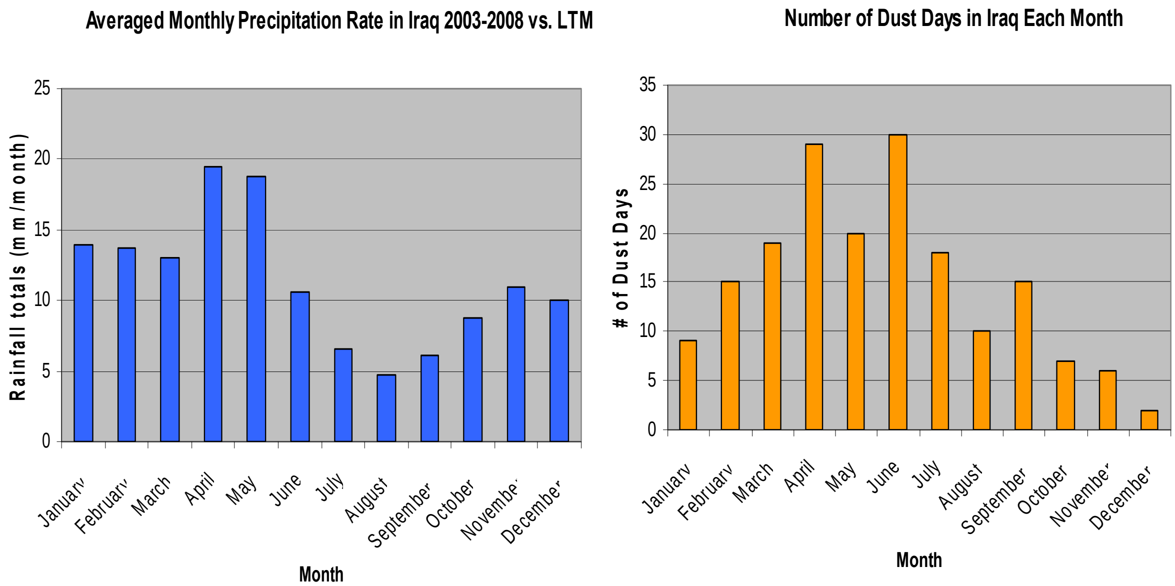

Figure 19. Monthly PR and number of dust storm days in Iraq during 2003–2008.

We also examined the surface wind direction associated with Iraq dust storm days. As we noted in Chapter I, several types of Iraq dust storms are associated with northwesterly and westerly winds (e.g., Warner 2004; Liu et al., 2007). Figure 20 shows for 2003-2008 in Iraq the number of dust storm days for each of eight wind directions. The most common wind direction during dust storms was northwesterly (from the northwest), with e second most common direction being southeasterly. This result and the results discussed in the prior

paragraph indicate that long range forecasts of northwesterly and southeasterly winds, plus long range forecasts of PR, could be useful in long range forecasting of dust storms in Iraq.

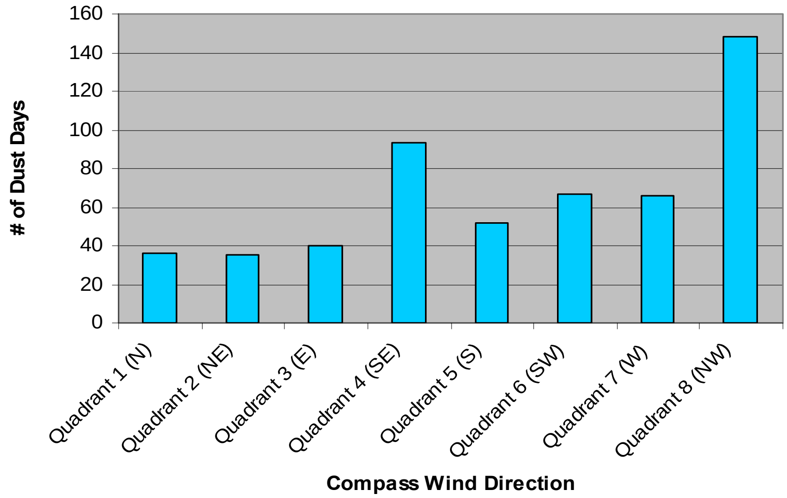

Figure 20. Number of dust storm days by surface wind direction during the dust storm days. The wind directions shown indicate the direction from which the wind came (e.g., Quadrant 8 (NW) indicates wind from the northwest). Note that northwesterly winds are the most common during dust storm days.

B. CONDITIONAL COMPOSITES

We focus on wind speed and direction as well as low precipitation rate (top two environmental factors from Table 2) using conditional composites of Iraq PR, SLP, and TKI.

1. PR Composites

Figure 21 shows the LTM, conditional composites, and anomalies of PR in the 30 days prior to Iraq dust storms during fall-winter 2003–2008. These figures indicate that PR tends to be below normal over much of Iraq prior to dust storms. The corresponding results for fall and for winter (not shown) were very similar, so we combined them into results for fall-winter. For similar reasons, we also

combined the corresponding spring and summer results into spring-summer results. Thus, we combined the four seasons into two seasons: fall-winter (ONDJFM) and spring-summer (AMJJAS). For all months, the PR conditional composites and anomalies indicated anomalously low PR in Iraq in the 30 days prior to Iraq dust storms. These results confirmed our hypothesis that a negative PR anomaly is an important pre-condition for dust storm formation.

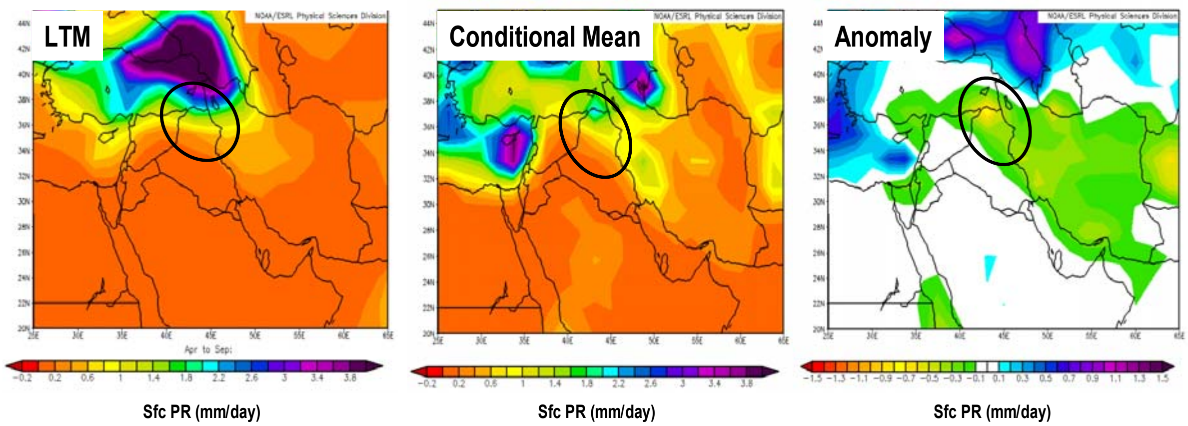

Figure 21. LTM (left), conditional composite mean (middle), and anomaly (right) for PR (in mm/day) in and near Iraq for all 30 day periods preceding dust storms days during October–March of 2003–2008 (ESRL 2009). Note the anomalously low precipitation in northeastern Iraq prior to the dust storms.

The LTM panel of Figure 21 shows that Iraq PR is concentrated in the mountains and upland plains, but the anomaly panel shows that these are also the regions in which PR is anomalously low prior to dust storms. This is significant because: (1) the mountains are a major source of water for the upland plans and alluvial plains, including the marshes in the alluvial plains; and (2) the upland plains and alluvial plains contain a large number of dust sources (see Figures 4-6, 10). So anomalously low PR in the mountains and upland plains is likely to lead to drier conditions in a large number of Iraqi dust source regions, including some where PR may not be anomalously low.

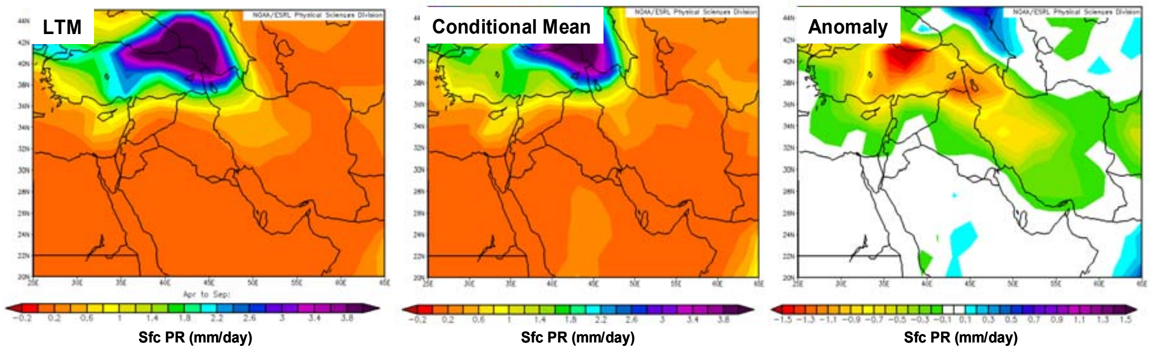

Figure 22. LTM (left), conditional composite mean (middle), and anomaly (right) for PR (in mm/day) in and near Iraq for all 30 day periods preceding dust storms days during April–September of 2003–2008 (ESRL 2009). Note the anomalously low precipitation in most of Iraq, and especially northeastern Iraq, prior to the dust storms.

Figure 22 shows LTM, conditional composites, and anomalies of PR in the 30 days prior to Iraq dust storms during spring-summer 2003–2008. Note the low LTM PR over most of Iraq, due to the position of the storm tracks to the north of Iraq. The conditional mean PR shows almost all of Iraq received little or no precipitation in the 30 days prior to dust storms. This result is more obvious in the anomaly figure, which shows that most of Iraq, and especially northeastern Iraq, experienced negative PR anomalies prior to the dust storms. Note also that the negative PR anomalies also occurred in Syria where dust sources for Iraq dust storms occur (see Figure 10).

2. SLP Composites

As discussed in section E.3 of Chapter I, a key factor for dust storms is the wind that blows over and away from dust sources. As shown in section A, Chapter III, the most common low level winds during Iraq dust storms are from the northwest. Figure 23 shows the LTM SLP, and conditional mean SLP and SLP anomalies during fall-winter dust storm days in Iraq. The LTM SLP indicates that the low level LTM winds are weak and from the southeast. The conditional mean SLP shows that the low level winds during dust storms are from the northwest in western Iraq and from the southeast in eastern Iraq. The SLP

anomaly indicates that low level wind anomalies are northwesterly and westerly over most of Iraq during dust storms. These conditional mean and anomalous winds, along with the corresponding PR results (see Figure 21), indicate that during fall-winter dust storms in Iraq, a large number of dust sources in Syria and the upland and alluvial plains of Iraq are likely to be available to support the dust storms, due to the wind and precipitation anomalies.

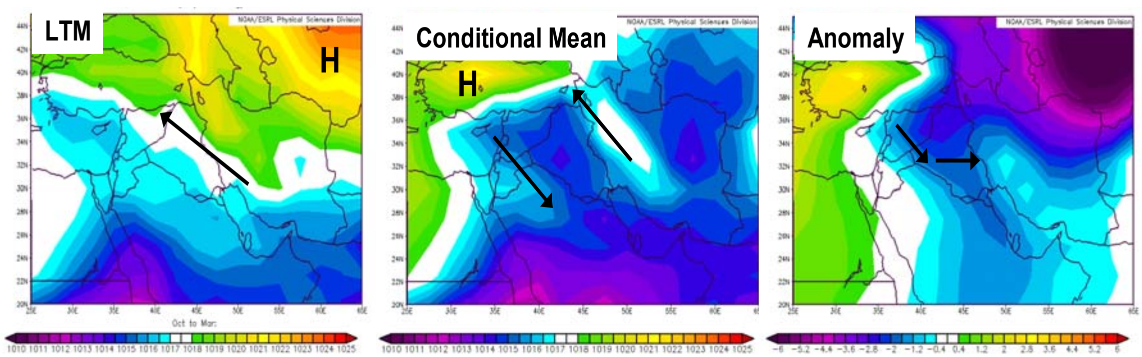

Figure 23. LTM (left), conditional composite mean (middle), and anomaly (right) for SLP (in hPa) in and near Iraq for all 30 day periods preceding Iraq dust storms days during October–March of 2003–2008 (ESRL 2009). Arrows indicate implied low level wind directions. Note the implied northwesterly and westerly wind anomalies over most of Iraq during dust storms.

The SLP anomalies shown in Figure 23 indicate that dust storms are associated with an anomalously weak Asian High northeast of Iraq and higher than normal SLP over the Mediterranean Sea and North Africa west of Iraq. To represent this SLP anomaly pattern and the associated wind anomaly pattern over and near Iraq, we constructed a SLP index, the TKI (section B.4-5 of Chapter II). A positive (negative) TKI corresponds to anomalously high (low) SLP near Tunisia (Kazakhstan) and northwesterly (southeasterly) wind anomalies over Iraq. The SLP anomaly pattern corresponds to a strong positive value of the TKI. Because of the association of this SLP anomaly pattern with dust storms, we can use positive vales of the TKI as a proxy for Iraq wind anomalies that are favorable for dust storms in Iraq.

Figure 24 shows the LTM SLP, and conditional mean SLP and SLP anomalies during spring-summer dust storm days in Iraq. The LTM SLP shows a narrow region of low SLP extending from the southeast into Iraq, with implied low level winds from the northwest or east over most of Iraq. The conditional mean SLP shows an amplification of the LTM pattern, with the narrow region of low SLP extending further into Iraq. The SLP anomaly indicates that low level wind anomalies are northerly or northwesterly over most of Iraq during dust storms. These conditional mean and anomalous winds, along with the corresponding PR results (see Figure 22), indicate that during spring-summer dust storms in Iraq, a large number of dust sources in Syria and the upland and alluvial plains of Iraq are likely to be available to support the dust storms, due to the wind and precipitation anomalies. Note that these spring-summer results are very similar to the corresponding fall-winter results.

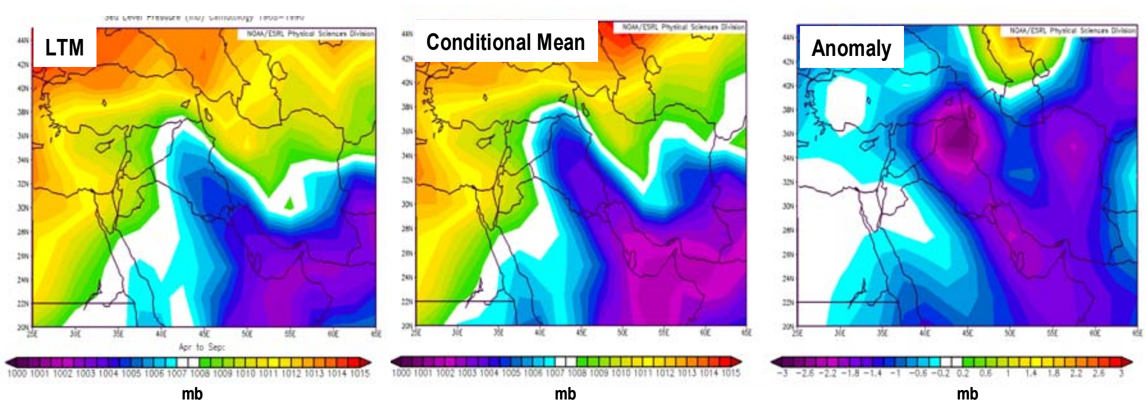

Figure 24. LTM (left), conditional composite mean (middle), and anomaly (right) for SLP (in hPa) in and near Iraq for all 30 day periods preceding Iraq dust storms days during April–September of 2003–2008. Note the implied northwesterly and westerly wind anomalies over most of Iraq during dust storms.

3. TKI

We developed the TKI as a means for concisely describing the winds over Iraq in a form that lends itself to use as a predictand of the winds that affect the

potential for dust storm activity. Figure 25 shows a time series of the TKI for March of 1970-2003. As discussed in the prior sections of Chapter III, positive values of the TKI are favorable for dust storms in all months.

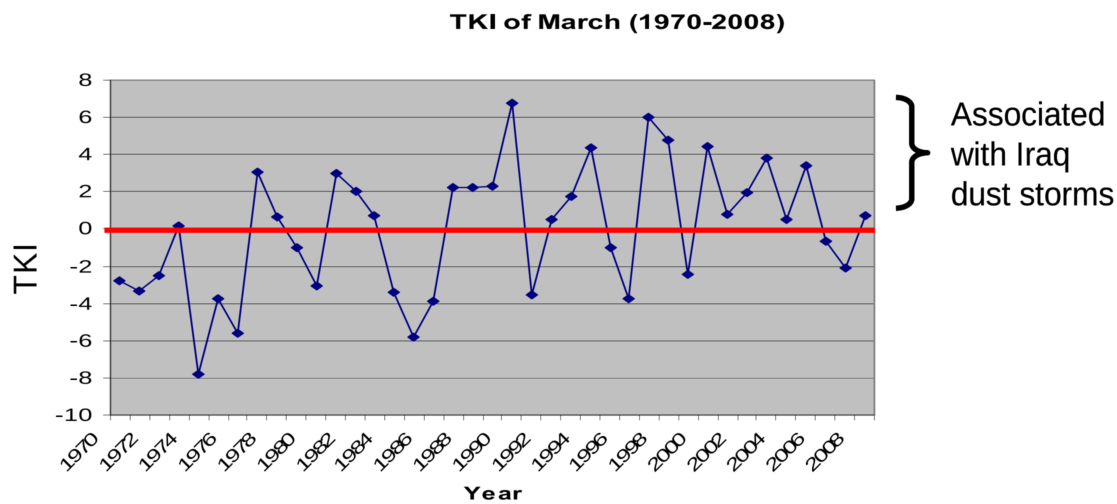

Figure 25. TKI time series (in hPa) for March of 1970 – 2008. The red line indicates zero on the vertical axis. Positive (negative) TKI values indicate northwesterly (southeasterly) low level wind anomalies over Iraq. Northwesterly wind anomalies are favorable for dust storm activity in Iraq. Note the positive trend in the TKI during 1970–2008, indicating a long term trend toward more dust storm favorable winds.

The TKI indicates variations from normal SLPs such that:

1. A positive TKI indicates Tunisia SLP anomaly > Kazakhstan SLP anomaly, which indicates, for: (a) fall-winter over Iraq, weaker than normal winds from the southeast, lower than normal wind speeds, and more frequent than normal occurrences of winds from the northwest; and (b) for spring-summer stronger than normal winds from the northwest, higher than normal wind speeds, and more frequent than normal occurrences of winds from the northwest,

2. A negative index indicates Tunisia SLP anomaly < Kazakhstan SLP anomaly, which indicates for: (a) spring-summer over Iraq, stronger than normal winds from the southeast, higher than normal wind speeds, and less frequent

than normal occurrences of winds from the northwest; and (b) weaker than normal winds from the northwest, lower than normal wind speeds, and more frequent than normal occurrences of winds from the southeast.

The general upward trend in the TKI over the last 40 years indicates that winds from the northwest have become more common, which means that the large scale Mediterranean-Asian circulation has become more favorable for the northwesterly winds associated with Iraq dust storms. If the TKI is predictable, then we should be able to predict the potential for dust favorable winds in Iraq.

C. CORRELATIONS

We calculated correlations between Iraq PR and global SST with SST leading PR by zero, one, and two months. Figure 26 shows a sample of these correlations for January and February SSTs in Indian Ocean and western Pacific correlated with March PR in Iraq. As discussed in Chapter II, correlations with magnitudes greater than 0.314 are significant at the 95% level. The red boxes in Figure 26 highlight areas of strong and significant negative correlations (shown in purple). These correlations indicate that when the SST in these regions increases (decreases) in Jan and Feb, Iraq PR tends to decrease (increase) in March. Thus, winter SST in northern and eastern IO may be a useful predictor of spring PR in Iraq. As shown in Figure 19, there is a tendency for high dust storm activity in Iraq in the spring. Thus, a winter predictor of dust storm favorable conditions in the spring could be very useful in operational planning.

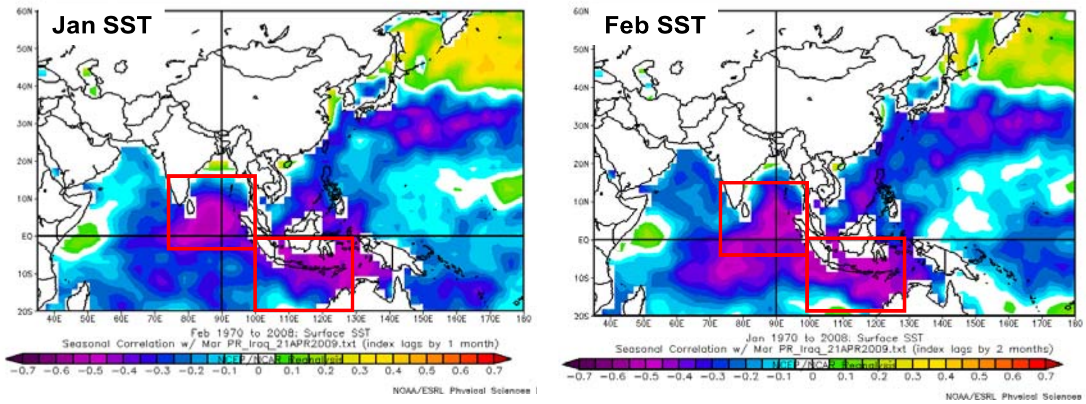

Figure 26. Correlations between the Jan and Feb SST versus Iraq PR in March based on data from March 1970–2008 (ESRL 2009) The red boxes highlight strong significant negative correlations and the regions we used for constructing SST predictor time series for use in the CAF process.

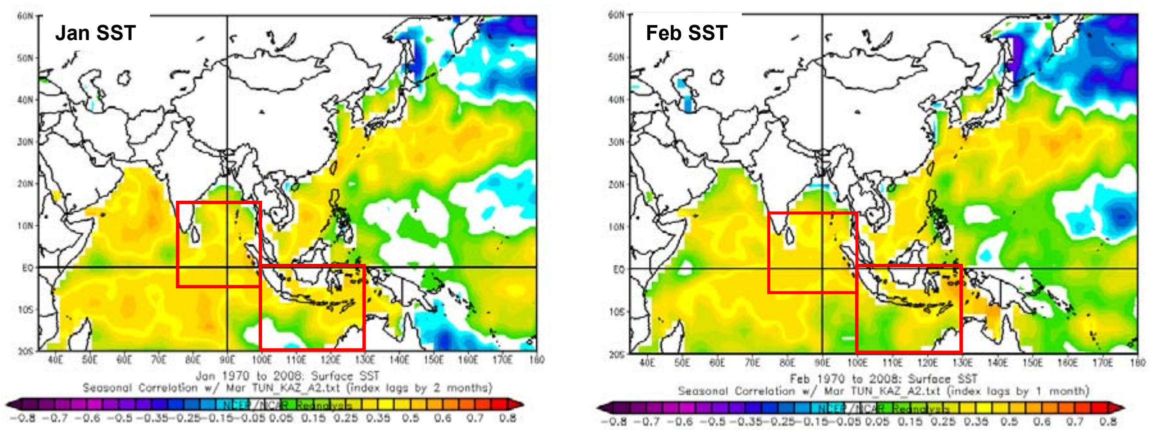

Figure 27. Correlations of SSTs in January and February with the TKI (ESRL 2009). Note positive correlations at one and two month lags. The TKI is statistically significant in the regions used. The correlations will be applied to the CAF.

Figure 27 shows a sample of the correlations of the TKI with global scale variables—in this case, the correlation of the TKI in March with SST in January and February. Correlations with magnitudes greater than 0.314 are significant at the 95% level. The red boxes in Figure 27 are the same as in Figure 26 and highlight areas of strong and significant positive correlations (shown in yellow and orange). These correlations indicate that when the SST in these regions

increases (decreases) in January and February, the TKI tends to increase (decrease) in March. Thus, winter SST in northern and eastern IO may be a useful predictor of spring TKI and low level winds in Iraq. As shown in the previous two sections, a positive TKI is favorable for dust storm activity in Iraq. So, winter SST in the Indian Ocean area highlighted by the red boxes in Figures 26 and 27 may be useful CAF predictors of dust storm favorable conditions in Iraq in the spring.

D. COMPOSITE ANALYSIS FORECASTS

We used our correlation results to develop composite analysis forecasts (CAFs) of Iraq precipitation rate (PR) and the TKI using the CAF process outlined in Chapter II.

1. Composite Analyses of Iraq PR Using Indian Ocean (IO) SSTs

Figure 28 shows the composite analysis for Iraq PR in March and northern tropical IO SST in February. The statistically significant results, highlighted in green, are for NN SST and AN PR; NN SST and NN PR; BN SST and AN PR; and BN SST and NN PR. We obtained similar results when using January SST as a predictor (not shown).

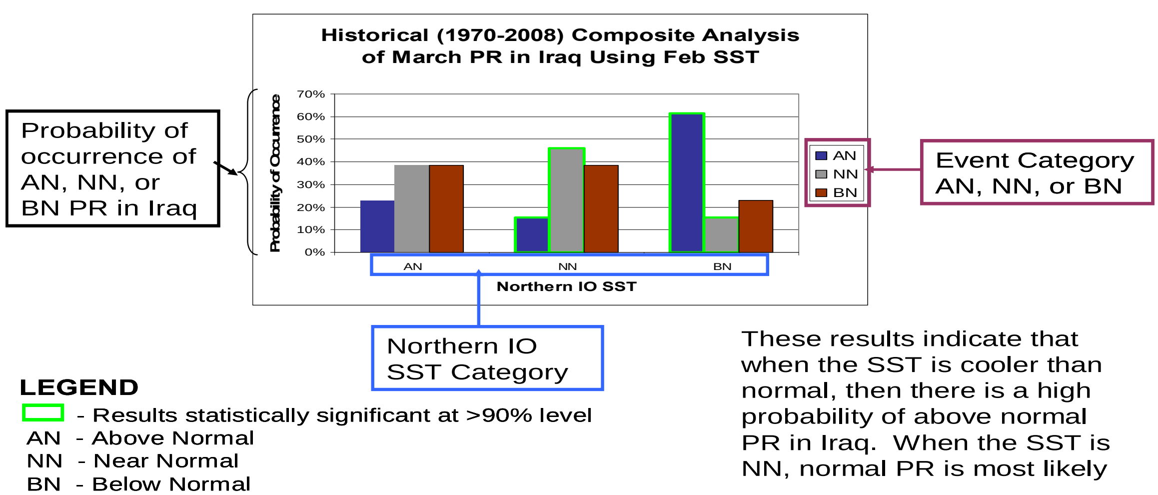

Figure 28. The composite analysis for March PR in Iraq using the northern tropical IO SST in February as the predictor. The statistically significant results are outlined in green.

Figure 29 shows the composite analysis for Iraq PR in March and eastern tropical IO SST in February. The statistically significant results, highlighted in green, are for AN SST and NN PR; AN SST and BN PR; BN SST and AN PR; and BN SST and BN PR. We obtained similar results when using January SST as a predictor (not shown).

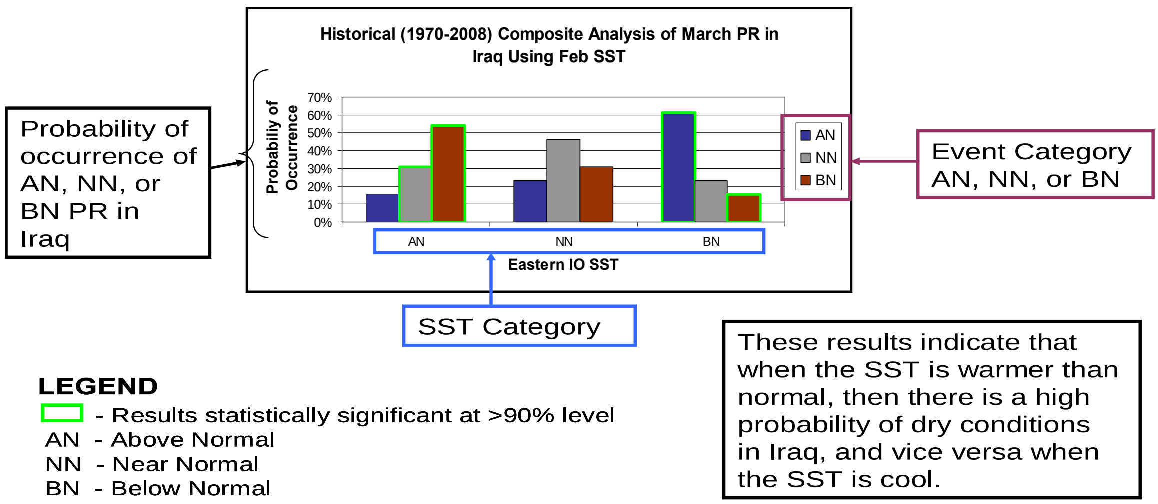

Figure 29. The composite analysis for March PR in Iraq using the eastern tropical IO SST in February as the predictor. The statistically significant results are outlined in green.

These composite analysis results (e.g., those in Figures 28 and 29) indicate that there is potential for skillful long range CAFs of Iraq PR in March using tropical IO SST in the prior two months as a predictor. These results also support our main hypotheses for this study (see section H, Chapter I) and are encouraging for our work to develop skillful long range forecasts of the potential for dust storms in Iraq.

2. Composite Analyses of TKI Using Indian Ocean SSTs

Figure 30 shows the composite analysis for the TKI in March and eastern tropical IO SST in February. The statistically significant results, highlighted in green, are for AN SST and BN TKI; AN SST and AN TKI; NN SST and NN TKI; BN SST and BN PR; and BN SST and NN TKI. We obtained similar results

when using January SST as a predictor (not shown). These composite analysis results indicate that the CAF process may be used to generate skillful long range forecasts of dust storm favorable winds in March in Iraq using IO SST in February as the predictor.

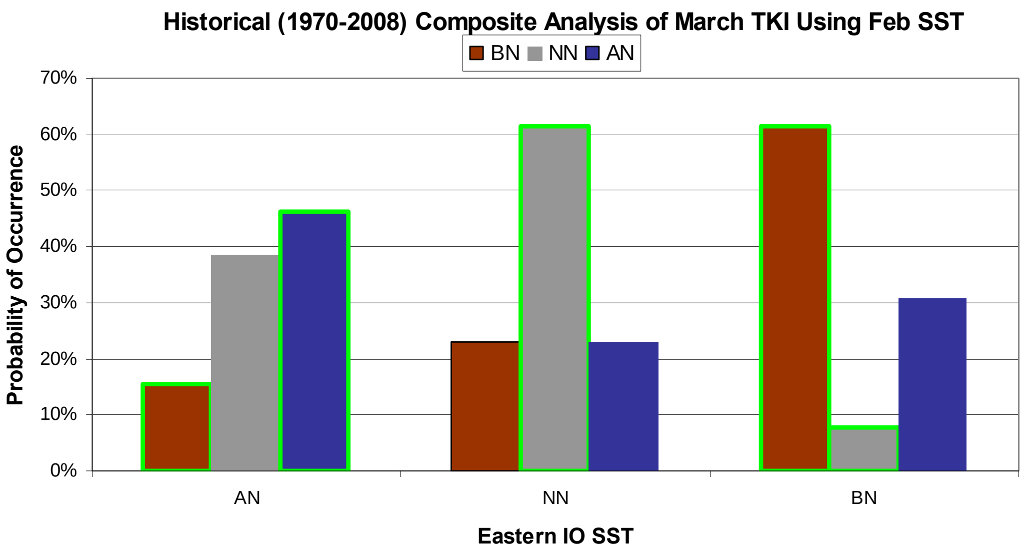

Figure 30. The composite analysis for March TKI using the eastern tropical IO SST in February as the predictor. The statistically significant results are outlined in green.

E. HINDCAST CAF OF MARCH 2005 CONDITIONS

Based on our composite analysis results, we applied the CAF process to produce hindcasts of Iraq PR and TKI. Figures 31 and 32 show sample results from hindcasts we conducted for March 2005. For these hindcasts, we used both the northern and eastern tropical IO SST in January and February 2005 as the predictors. Figures 31 and 32 show the results when using the eastern tropical IO SST in February 2005 as the predictor. At that time, the eastern tropical IO SST was in the AN category. Applying the statistical analysis based on AN SST conditions, our CAF shows a high probability for dry conditions as well as northwesterly winds for the Iraq area (right panels of Figures 31 and 32).

Because there is a higher probability of these dust storm favorable conditions, we would have inferred that March 2005 had higher than normal probability for dust storm activity.

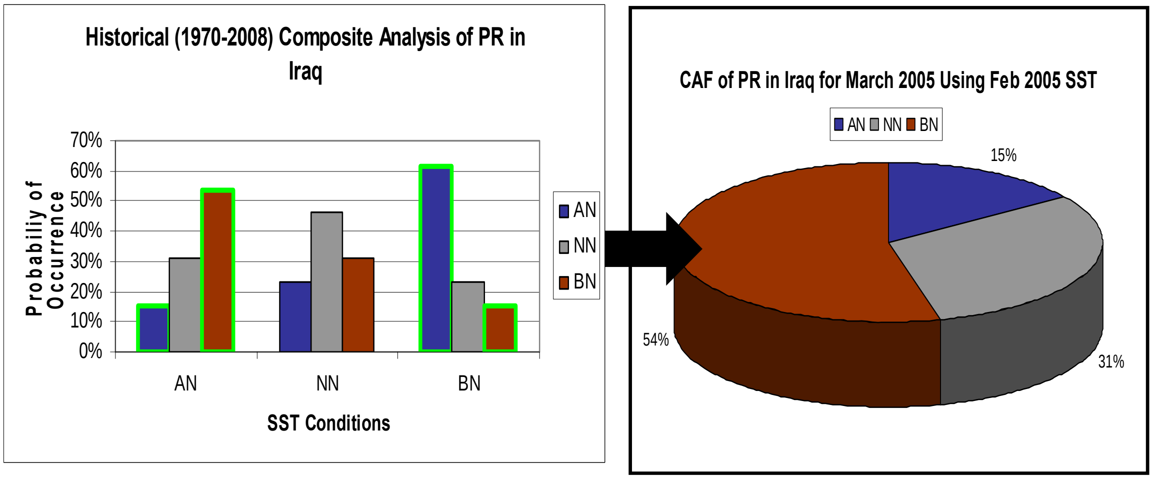

Figure 31. Left panel: The composite analysis for March PR In Iraq using the eastern tropical IO SST in February as the predictor. The statistically significant results are outlined in green. Right panel: The corresponding probabilistic long range hindcast of Iraq PR in March 2005 based on AN SST in the eastern tropical IO in February 2005. Note the higher than normal probability of BN PR.(54%) and the lower than normal probability of AN PR (15%). This hindcast indicates a weighting of the climate system toward dust storm low Iraq PR in March 2005 and thus dust favorable conditions for April 2005.

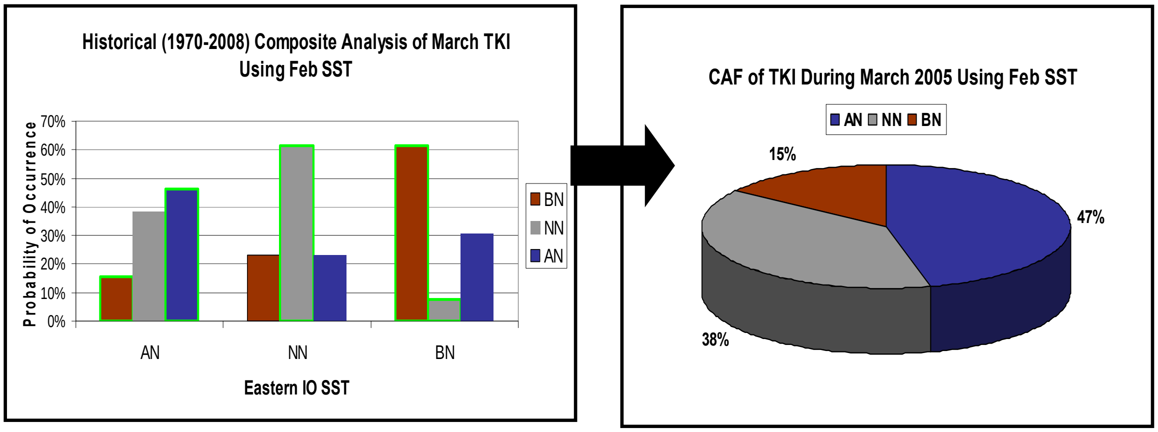

Figure 32. Left panel: The composite analysis for March TKI using the eastern tropical IO SST in February as the predictor. The statistically significant results are outlined in green. Right panel: The corresponding probabilistic long range hindcast of TKI in March 2005 based on AN SST in the eastern tropical IO in February 2005. Note the higher than normal probability of AN TKI.(47%) and the lower than normal probability of BN TKI (15%). This hindcast indicates a weighting of the climate system toward dust storm favorable low level winds in March 2005.

Figure 33 shows the SST anomalies during February 2005, and the Iraq region PR and SLP anomalies conditions during March 2005.

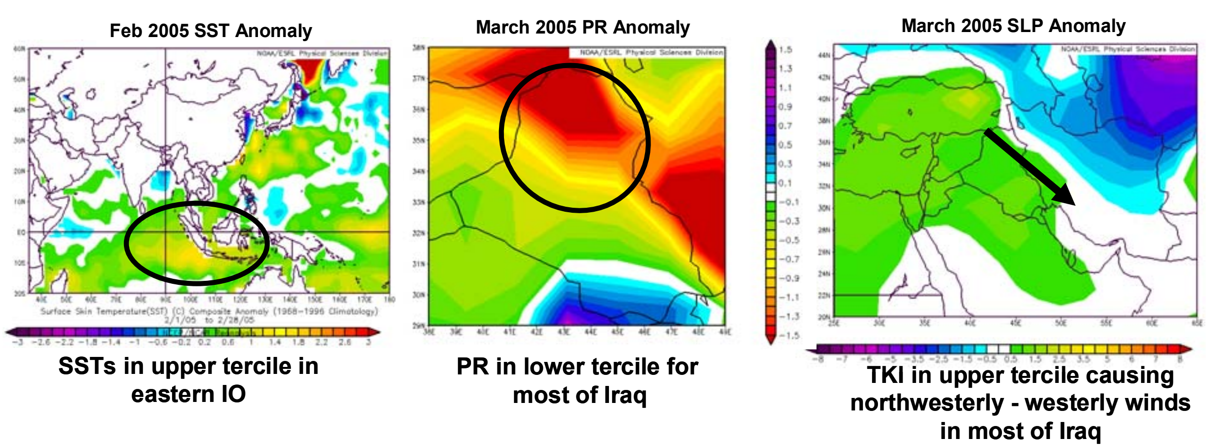

Figure 33. Indian Ocean SST anomalies in February 2005 (left panel), Iraq PR anomalies in March 2005 (center panel), and Southwest Asia SLP anomalies in March 2005. (ESRL 2009)

The February 2005 SST in the eastern tropical IO fell into the upper tercile, as did the March 2005 TKI. The March 2005 Iraq PR was in the lower tercile. This is consistent with the hindcasts from the CAF process that were weighted toward low PR and high TKI (Figures 31–32). Thus, overall, the forecast was good for the general region of Iraq. However, the implied low level wind anomalies were centered over eastern Iraq and western Iran, and thus not as dust storm favorable for Iraq as they would have been had they been centered over central Iraq. The six stations in Iraq reported five days of dust during March 2005, which is 25% higher than the average for all March months during 2003–2009. Interestingly, observations from near Iraq (specifically Jordan, Syria, Iran and Kuwait) indicated dust for 13 days in March 2005 (NRL 2005). This and other hindcasts using the CAF process indicate the CAF method has promise as a tool for long range forecasts of dust favorable conditions in Iraq. More extensive hindcasts and forecasts using CAF method need to be done and verified. Additional tools for accounting for multi-year trends in predictors and predictands also need to be incorporated (as discussed in Chapter IV).

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IV. SUMMARY AND RECOMMENDATIONS

A. SUMMARY

The goal of this research was to identify dust favorable factors that can be predicted at long lead times (two weeks or longer). We examined dust observations for Iraq from 2003–2009 to determine the environmental factors associated with dust storms. We analyzed the factors to identify those with a high potential for long range prediction. The two factors we selected were Iraq precipitation rate (PR) in the 30 days prior to dust storms and low level winds. We tested three large scale factors as potential predicators of the Iraq factors: an index of ENLN, SST in the northern tropical Indian Ocean, and SST in the eastern tropical Indian Ocean. We identified Indian Ocean SST as a potential predictor of Iraq precipitation and wind predictands. We tested for statistical significance at the 90% level for the relationships between the predictors and predictands using the composite analysis method. Predictors that passed this statistical test were used to produce hindcasts using the CAF process, which served as case studies for our long range forecasting methods. Our results indicate that skillful long range forecasts of dust storms in Iraq may be possible via prediction of Iraq precipitation and low level winds. Additional research needs to be done to account for long term trends in predictors and predictands (e.g., regression, optimal climate normals).

B. RECOMMENDATIONS FOR FUTURE RESEARCH

We recommend expanding our study to include multi-decadal analyses and hindcasting for all seasons. We also recommend conducting similar studies for dust storms in other regions (Afghanistan, Horn of Africa, etc). A third research recommendation is to identify the impacts of additional climate variations and global climate change on Iraq dust storms. This would include: (1) examining further the role of global scale climate variations, including the MJO

and IOZM; and (2) investigating the importance of accounting for long term trends in the predictors and predictands in improving long range forecast skill. This could be accomplished using, for example, linear regression and using optimal climate normals. Figure 34 shows a long term increase in the March TKI indicated by the polynomial fitted curve. Information about that increase has the potential to be useful in improving long range forecasts of Iraq winds. Regression and optimal climate normal methods could be used to exploit that potential for improving forecast skill (cf. van den Dool 2007).

Figure 34. TKI (circles in hPa) in March from 1970–2008 and the corresponding long term increase in the March TKI. (curved line). The curved line represents a polynomial fit to the TKI. Note the large percentage increase since 1970 in the March TKI. From personal communication with David Meyer, Operations Research Department, Naval Postgraduate School (2009).

C. RECOMMENDATIONS TO DEPARTMENT OF DEFENSE (DOD)

We recommend that DoD develop long term dust storm data sets for areas of DoD interest and make the data available online through standard METOC sources. We also recommend that DoD develop an operational capability to produce advanced climate analyses and long range forecasts of the potential for dust storm activity based on state of the science data sets and methods. The DoD should also incorporate modern climate analysis and long range forecasting concepts and methods into METOC education, training, and professional development programs.

As discussed in Chapter I, the DoD does not produce forecasts for dust storms at long lead times (two weeks and longer) for Southwest Asia or other areas of interest. The CAF process should be investigated further to better assess its potential or use in producing such forecasts. The data resources for producing the CAF are available from NCEP and other civilian operational centers. A key investment in this effort would be in developing a standard operating procedure (SOP) for forecast production, and in training and educating personnel to conduct climate analyses and long range forecasting. The return on those investments would be realized by decision makers who would use the dust forecasts to inform and improve decisions that must be made months in advance.

We also recommend that a study of weather-sensitive, long lead DoD decisions be done to identify the optimal ways for producing and delivering long range forecasts to military planners. Our final recommendation is for DoD climatology centers to develop and maintain a multi-decadal dust storm data set. We used six years of data but many additional years are needed to describe the major temporal and spatial patterns in dust storm activity. Continual and intentional collection of dust occurrences should be mandated and the data should be made widely available from standard DoD climatological data sources.

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